COSTS OF MANIPULATING INFORMATION IN VISUAL WORKING MEMORY

by

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Abstract

Our internal representation of a complex visual scene relies on the dynamic processing of information in visual working memory (VWM). Though traditional methods have focused on storage limitations, here I move beyond these issues to explore cognitive abilities for dynamically manipulating information in VWM. To this end, I developed a novel task in which participants are presented with a memory display consisting of colored circles, whose colors disappear to leave behind circular placeholders. Pairs of placeholders swap positions a varying number of times, after which participants judge the hidden color of a probed placeholder. This task is analogous to static change-detection, along with a manipulation component that requires the updating of spatial-feature bindings of objects as they engage in smooth motion. In Experiments 1-4, I investigated whether there are any costs associated with manipulating information in VWM. To this end, I varied set size (2, 3, or 4 placeholders) and number of swaps (0-4 swaps). A systematic impairment of memory was observed for manipulating 3-4 items that increased with swaps. In contrast, performance with 2 items was unaffected by swaps. In Experiments 5-7, I demonstrated that manipulating information in VWM does not affect information that is strictly stored in this system. Relatedly, I investigated the inverse of this relationship in Experiments 8-9, and demonstrated that information load, a factor known to limit storage capacity, does not additionally constrain manipulation ability. These results suggest that VWM storage and manipulate operate on two separate representations. In a dynamic world, the mind requires the ability to dynamically

manipulate working memory representations – not merely the ability to passively store static representations.

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Chapter 1: Introduction

1.1 Working memory - function and importance

After each given moment, the visual world as we know it ceases to exist. Objects move across time and space, are subjected to featural changes, and disappear from our line of sight. To impose stability onto our experiences of the dynamic world, cognition employs a working memory (WM) system that serves two essential functions. First, it provides a way to selectively store and quickly access mental representations of objects that are no longer in direct perception. Second, it supports an ability to actively manipulate these representations. These manipulations refer to the set of computations through which stored information is reorganized or updated in the face of new information (Veltman, Rombouts, & Dolan, 2003). Based on these functions, WM is recognized as a essential part of complex cognition (Anderson et al., 1997; Meyer and Kieras, 1997; Conway et al., 2005; Cowan, 2005), and has been linked to various constructs, such as fluid intelligence (Fukuda et al., 2010; Kane, Bleckly, Conway, & Engle, 2001; Kyllonen & Christal, 1990), attention (Hollingworth, Matsukura, & Luck, 2013; Mannan et al., 2010; Woodman, Luck, & Schall, 2007), and comprehension/reasoning (Daneman & Carpenter, 1980; King & Just, 1991; Swanson & Berninger, 1995).

We constantly use the abilities to store and manipulate information in WM to guide intelligent behavior. When we move our eyes while viewing a display, we use WM to temporarily store snapshots of the scene (taken at different time points and perspectives) and fuse them to build an integrated representation (Irwin, 1991; Hollingworth & Henderson, 2002). When we learn novel words or a different language, we temporarily store unfamiliar phonological sounds in WM, while we scaffold such information onto existing knowledge (Baddeley, Gathercole, & Papagno, 1998). When a car enters our blind spot while driving, we're able to store a representation of that vehicle and dynamically update its position in memory over time, even while it is no longer visible, based on the previously viewed trajectory.

In short, the abilities to store and manipulate information in WM support a variety of basic and complex operations, including the abilities to reason about objects that are no longer visible (Flombaum & Scholl, 2006; Shinskey & Munakata, 2003), to solve complex problems (Libertus, Brannon, & Pelphrey, 2009; Hitch & McAuley, 1991; Engle, Tuholski, Laughlin, & Conway, 1999), update quantity information (Feigenson & Yamaguchi, 2009), among many others.

Much attention has been placed on investigating constraints that affect WM, as these constraints may have significant consequences throughout mental life. However, relatively less emphasis has been placed on exploring limitations in manipulation ability, as opposed those in storage. Studies within the verbal domain suggest that there are costs associated with manipulating information, and that these costs are independent of those for storage. However, this topic remains unexplored within the visual domain. **Are there costs associated with manipulating visual information in WM? And if so, how do these costs relate to those associated with storing information within the system?** My dissertation will focus on investigations these questions.

1.2 Overview of Chapter 1

In the remainder of this chapter, I will provide an overview of the WM literature. In Section 1.3, I will describe key properties of the WM system and provide evidence supporting the distinction between WM and other memory systems. In Section 1.4, I will review current theories of the architecture of WM and provide evidence warranting the subcategorization of the system into independent components: verbal WM and visual WM. I will then review evidence describing factors that have been suggested to affect capacity limits and manipulation costs (Section 1.5), including limits on verbal WM storage capacity (Section 1.5.1) and verbal WM manipulation ability (Section 1.5.2), and describe the extent to which these abilities are (in)dependent of one another. Lastly, in Section 1.5.3, I will provide an overview of the costs associated with storing information in visual WM, and will move towards the focus of my dissertation: investigating whether or not costs exist with manipulating information in visual WM and how these costs may relate to those for storing information within the system.

1.3 Hallmark characteristics of WM: distinctions from other memory systems

Quite often, the terms "working memory" (WM) and "short-term memory" (STM) are used interchangeably when referring to the temporary maintenance of information over short intervals (seconds). These constructs are arguably identical, with the exception that the term "WM" additionally encapsulates the concept of goal-driven manipulation of stored information (Courtney, 2010). Throughout this dissertation, I will therefore use the term “WM storage”, instead of STM, when referring to the passive storage of information within the general WM system.

Working memory, however, is distinct from other memory systems, such as iconic memory (IM) and long-term memory (LTM). During information processing, input from the senses is initially stored in IM, after which such information can be transferred to WM, and then onto LTM (Luck & Hollingworth, 2008). Despite such interdependence, WM differs from these constructs based on fundamental properties that have come to define this system.

At first pass, distinctions between WM and LTM can be drawn based on whether information is stored over short vs. long periods of time. This, in turn, manifests as differences in (1) how information is coded within each system, (2) how much information can be stored in a given moment in each system, and (3) the neurological mechanisms supporting the underlying storage processes.

Similarly, distinctions can be drawn between WM and IM, by virtue of (1) how long information can be stored within each system, (2) how much information can be stored, and (3) the durability of these stored representations.

Here, I provide evidence warranting the distinctions made between WM and these other memory constructs. In so doing, I provide a profile of the WM system and describe its key attributes.

1.3.1 WM vs. LTM

Coding of Information:

The separation of memory into separable short-term vs. long-term stores stems from evidence demonstrating marked differences in how information can be remembered across varying delay periods. For example, the phonological similarity effect (Conrad, 1964; Conrad & Hull, 1964) is observed for shorter vs. longer delay periods, such that individuals are better able to immediately recall words that are semantically similar vs. phonologically similar (Baddeley, 1966a). In contrast, this effect reverses when individuals must retain this information over longer periods of time (Baddeley, 1966b).

Similar findings have been suggested to reflect differences in how information is coded over shorter vs. longer periods. For example, rehearsal processes (e.g. articulatory rehearsal, visual refreshing) may serve to maintain information over shorter periods of time (Baddeley & Hitch, 1974). In contrast, information maintained over longer periods may rely on semantic processes by which they come to be integrated into existing knowledge (Brady, Konkle, & Alvarez, 2011). Such differences in coding of information may allow for short-term memories to be more quickly accessible, formed rapidly, and subject to decay in the absence of rehearsal (Cowan, 2008; Gegenfurtner & Sperling, 1993; Shibuya & Bundesen, 1988; Vogel, Woodman, & Luck, 2006), compared to long-term memories (Atkinson & Shiffrin, 1971; Baddeley & Hitch, 1974; Cowan, 2008).

Capacity and Resolution:

Perhaps the strongest argument for discretizing memory into short-term vs. long-term systems comes from evidence demonstrating differences in how much information can be stored across varying delay periods.

Indeed, one of the hallmark characteristics of short-term memory is that it is markedly capacity limited. Since Miller's (1956) classical findings, various studies have demonstrated that the amount of information that is available for immediate recall is limited to a maximum of 4 items for visual stimuli (Cowan, 2001; Luck & Vogel, 1997; Phillips, 1974 Vogel, Woodman, & Luck, 2001) and 8 items for verbal stimuli (Brener, 1940). Moreover, a trade-off exists, such that the fidelity with which such information is maintained decreases, as more information is stored within the system (Alvarez & Cavanagh; Bays & Husain, 2008; Wilken & Ma, 2004; Zhang & Luck, 2008).

In contrast, long-term memory is characterized by its vast capacity (Atkinson & Shiffrin, 1971; Nickerson, 1965; Sheppard, 1967). Behavioral studies have demonstrated that individuals can remember up to ten thousand novel images with approximately 83% accuracy hours or days after being shown these items (Standing, 1973). Moreover, the fidelity with which such information is stored over long periods is strikingly rich (Brady et al., 2008; Konkle et al., 2010a), particularly when such information is scaffolded onto existing knowledge (Konkle et al., 2010b; Wiseman & Neisser, 1974).

Neurological Differences:

Differences exist among the neurological mechanisms that allow for information to be stored during short vs. long intervals.

It has been suggested that information is maintained over shorter periods of time via reverberant activity of the neuronal populations coding for these (perceptual) representations (Harrison & Tong, 2009; Hebb, 1949; Luck & Hollingworth, 2008; Serences et al., 2009). Such recurrent firing activity can be thought of as the neurological equivalent to cognitive rehearsal processes that determine capacity limits in WM. Information is maintained in this system for as long as this reverberant activity continues and the information is rehearsed. Support for this theory comes from single-neuron recordings from monkeys recorded during delayed response tasks, which demonstrate increased activity of neurons in the prefrontal cortex that may reverberate via excitation of synaptic loops (Funahashi et al., 1989; 1993; Fuster & Alexander, 1971; Goldman-Rakic, 1995; Hebb, 1949; Miller, Erickson, & Desimone, 1996).

In contrast, the storage of information over longer intervals engages the medial temporal lobe and produces structural changes in the brain via long-term potentiation (Cabeza & Nyberg, 2000; Hebb, 1949). This process can be thought of as neuronal growth, wherein the synaptic connections between neurons that code for a memory representation become strengthened via the stabilization of dendritic spines (Yoshihara, De Roo, & Muller, 2009; Roberts et al., 2010; Zuo et al., 2005). These structural changes may underlie the stability and durability of long-term memories.

Additionally, patient work demonstrating a double dissociation in memory recall over short vs. long delays supports the discretization of memory into separable systems (Drachman & Arbit, 1966; Scoville & Milner, 1957; Shallice & Warrington, 1970). For example, amnestic patients demonstrate in tact immediate memory recall in a digit span task, but impaired performance for delayed recall of recent events (Baddeley & Warrington, 1970). Similarly, H.M., an epileptic patient who underwent a bilateral medial temporal lobe resection, demonstrated successful recall of digits when such information was rehearsed for short periods of times, but was unable to do so over longer delays (Milner et al., 1968; Squire & Wixted, 2011). Conversely, the opposite pattern holds true for Parkinson's patients tested on the Weschler Memory Scale drawings test, who exhibit impaired performance over shorter retention periods compared to longer ones (Sullivan & Sagar, 1991).

1.3.2 WM vs. Iconic Memory

Duration:

Both WM and iconic memory (IM) can be distinguished from LTM based on restrictions that limit their storage processes to shorter durations. However, distinctions can be drawn among these systems based on the temporal windows over which they operate. Evidence from behavioral (Fukuda et al., 2010; Pasternak & Greenlee, 2005), computational modeling (Zhang & Luck, 2009), and primate (Keogh & Pearson, 2011) studies demonstrate that information can be actively maintained within WM for a period of seconds. In contrast, memory representations in IM are relatively fleeting and survive for up to 150 ms (Averbach & Coriell, 1961; Coltheart, 1980; Neisser, 1967; Phillips, 1974). These temporal parameters have primarily been estimated based on how much and how well information can be maintained over these periods of time.

Capacity and Resolution:

Initial support for the distinction between WM and IM was provided by Sperling (1960), who demonstrated that across very brief durations, individuals have access to amounts of information that exceed typical storage limits in WM. Across a series of experiments, Sperling (1960) instructed participants to remember a matrix of alphanumeric characters that were presented for approximately 50 ms. When asked to recall as many items as possible (whole report condition), participants were only able to recall between three and five items, consistent with the 3-4 item WM storage limit for visual information (Luck & Vogel, 1997; Mance & Vogel, 2013; Vogel, Woodman, & Luck, 2001). However, when instructed to recall a subset of items using a cued recall method (partial report condition), participants were able to report the majority of letters presented in the display.

Similarly, Phillips (1974) demonstrated differences in the amount of information that could be retained in memory over brief periods of time. He had participants complete a change detection task, in which two displays of block patterns were separated by a blank interval of varying temporal durations [interstimulus intervals (ISI): >1 s vs. 1-10 s]. In so doing, he found that memory recall was near perfect for shorter durations

(~250 ms), and declined systematically thereafter. Moreover, this decline in accuracy over increasing temporal intervals was compounded by information load.

Taken together, these findings demonstrate differences in the capacity and resolution of information for memories stored across brief durations. The, perhaps, infinite capacity and richness of representations stored in IM have led some to suggest that information stored within this system is an "icon" of the sensory stimulation that persists across very brief durations and is formed automatically (Emrich, 2011). In contrast, the relatively limited capacity and resolution of WM have fueled claims that information stored within this system is selective and goal-driven (Courtney, 2010).

Durability:

Information stored in WM and IM also differ markedly in terms of their durability. Phillips (1974) demonstrated this in a change detection experiment similar to the one mentioned above. However, instead of having stimulus displays always appear at the same location, the location of the second (test) display may have been spatially displaced. This change in spatial position caused significant decrements in memory accuracy for ISI's shorter than 100 ms (iconic memory), but not for those of longer durations (working memory). This suggested that the iconic representations, but not the working memory representations, lacked a durability that would support comparing them to information at a new retinal position.

Further distinctions in the durability of WM vs. IM representations can be based on the overwriting of these representations in the face of new visual input. For example, in Phillips' (1974) study, when a mask was presented during the ISI that interleaved the stimulus displays, performance accuracy significantly decreased for ISI's shorter than 100 ms, but not for longer durations. As such, representations stored in IM degrade in the face of visual interference, such as masks or visual transients (Averbach and Coriell, 1961; Gegenfurtner and Sperling, 1993; Phillips, 1974; Spencer, 1969; Turvey, 1973), whereas those stored in WM do not (Irwin & Thomas, 2008). Based on its insensitivity to visual interference and changes in the absolute and relative spatial positions of stimuli (Jiang, Olson, & Chun, 2000), WM allows us to maintain perceptual continuity throughout our experiences of the dynamic world. As such, WM representations are likely not to be retinotopically mapped.

1.4 Architecture of working memory

Evidence demonstrating such fundamental differences between WM and other memory systems has led to the rejection of unitary models of storage and set the stage for Baddeley's (1974; 2000) model of WM. Conceptually, this theory differs from its predecessors by virtue of its multiple storage and processing constituents.

The two processing components that preside over stored information, the central executive and the episodic buffer, constitute the "working" element of working memory. The central executive mediates between the modules, by directing the input and output of information to and from the stores. It is further involved in the execution of computations, including the manipulation of stored information and the division and direction of attention to tasks. Though the exact functions of the episodic buffer remain to be conclusively defined, it is depicted as an integrator of multidimensional information into a single representation. As such, it is believed to connect WM to perception and LTM, and support abstract thought.

Under this framework, information is stored separately within modality specific modules, as opposed to within a single multidimensional unit. These modality specific subcomponents include the phonological loop, which maintains verbal and auditory information, and the visuospatial sketchpad, which maintains visual and spatial information. Based on their functions as storage repositories, they are colloquially referred to as verbal WM storage and visual WM storage, respectively. The interaction of these domain specific storage modules and processing components constitute the verbal WM and visual WM systems. This subdivision of general WM into separate subsystems is supported by evidence demonstrating independence between verbal and visual storage processes.

1.4.1 Independence among verbal and visual storage

Behavioral:

The argument of domain specificity in WM storage is supported by behavioral studies demonstrating double dissociations in memory performance under concurrent verbal and visual loads. Results from these studies show that the ability to temporarily hold verbal information in memory remains unaffected under a concurrent visual load, though performance is greatly disrupted when the load is also verbal in format.

Conversely, the storage of visual information is unaffected by a concurrent verbal, but not visual, loads.

This pattern is observed across a variety of paradigms, including tasks where participants are instructed to 1) recall a sentence or line diagram while verbally or visually signaling about the information (Brooks, 1968), 2) memorize a list of verbal stimuli (digits or words) while subvocally articulating a sound/word (Baddeley & Hitch, 1974; Baddeley, Thomson, & Buchanan, 1975), 3) memorize a checkerboard while visually tracking a moving object or repeating a sequence of numbers (Cocchini et al., 2002), 4) compare two sequentially presented dot matrices while performing rote rehearsal of words vs. using a visual imagery mnemonic (Logie, 1995), 5) memorizing spatial or causal information about objects and their locations while responding to spatial or causal probes (Friedman & Miyake, 1990), 6) remembering featural and spatial information of objects in a grid while subvocally rehearsing digit words or performing a visual dot discrimination task (den Heyer & Barrett, 1971), and 7) comparing two sequentially presented displays of visual (colored squares) or verbal (uppercase letters) information while subvocally rehearsing digits (Vogel, Woodman, & Luck, 2001).

Further evidence for domain specificity in WM comes from correlational studies demonstrating differential relationships between individual differences in verbal and visual storage abilities (Alloway, Gathercole, & Pickering, 2006; Daneman & Tardif, 1987; Morrel & Park, 1993; Friedman & Miyake, 2000). For example, estimates of visual storage ability, as measured by the Flicker change detection task, correlate with other measures of visual storage, such as the Corsi block task, but not with verbal measures, such as the digit and letter span tasks (Pailian et al., 2013). Conversely, verbal storage ability as measured by the digit span task correlates with performance observed in a letter span task, but not with performance in a Flicker change detection or Corsi block task. This double dissociation is also observed in work conducted by Shah and Miyake (1996) who demonstrated that performance on a verbal span task is significantly more predictive of verbal SAT scores than a visual memory task, whereas the latter is more highly correlated with other indices of visuospatial ability, compared to a verbal storage task.

Neurological evidence:

Lesion Studies

Lesion studies have been instrumental towards establishing domain specificity in WM by demonstrating associations between separate brain regions with verbal and visual storage.

In a study of over 600 patients with unilateral cerebral lesions, Warrington, James, and Maciejewski (1986) observed lesions occurring in the left hemisphere for patients demonstrating poor performance in a WAIS digit span task. These results were further replicated by Della Sala and Logie (1993), who conducted a meta-analysis of patients with verbal storage impairments, as measured by a variety of paradigms. They, too, observed a relationship between verbal memory storage ability and lesions occurring in the *left* hemisphere. Specifically, these lesions were observed at the junction of the inferior parietal lobe and superior posterior temporal lobe. Advances in localization techniques have more precisely identified the supramarginal gyrus as the locus of damage associated with impaired verbal storage ability (Warrington, Logue, & Pratt, 1971).

In contrast, impairments to visual storage ability seem to be associated with damage to the *right* hemisphere. De Renzi & Nichelli (1975) first identified this link in a study of patients with impaired performance on a task of short-term visual storage but unimpaired performance on tasks of long-term visual and short-term verbal storage. This association has been observed in independent studies by De Renzi, Faglioni, and Previdi (1977), as well as Hanley, Young, and Pearson (1991), who have each found that patients with damage to the posterior region of the right hemisphere exhibit impaired performance on a Corsi block task of visual memory storage, compared to healthy controls. Unfortunately, relative to studies of verbal storage, lesion studies have not been able to identify the exact locus of damage that leads to impairments in visual storage (Baddeley & Logie, 1999).

<u>Neuroimaging:</u>

Neuroimaging studies provide converging evidence of independence between verbal and visual storage abilities in working memory (Owen et al., 1998; Smith et al., 1996). For example, Paulesu, Frith, and Frackowiak (1993) and Salmon et al. (1996) measured brain metabolism levels using positron emission tomography (PET) during a task where English-speaking participants were instructed to memorize a list of English letters (engaging verbal storage abilities). Consistent with lesion studies, both investigations observed increased activation of the inferior left supra-marginal gyrus. In contrast, a PET investigation of visual abilities as measured by performance in a Corsi block task demonstrated increased activity in right parietal and frontal associative areas (Perani et al., 1993). Similarly, memory for spatial locations as measured by a spatial change detection task has been demonstrated to activate areas similar areas in the right hemisphere, including parietal, occipital, and prefrontal regions (Jonides et al., 1993).

Most notably, Smith, Jonides, and Koeppe (1996) demonstrated a double dissociation in brain areas showing higher activation under verbal vs. visual storage demands. Across three ‘n-back’ experiments (Exp 1: remember either names of letters or positions of dots; Exp’s 2 & 3: remember names of letters vs. location of letters), Smith and colleagues demonstrated greater activation in the left hemisphere for conditions requiring verbal WM storage and greater activation in the right hemisphere for conditions requiring visual WM storage.

Further evidence for the hemispheric lateralization of working memory storage stems from functional magnetic resonance imaging (fMRI) studies. For example, Rämä and colleagues (2001) conducted a delayed match-to-sample task where participants were instructed to remember unfamiliar names and faces. In so doing, they observed higher levels of activation in the left hemisphere (left insula/postcentral gyrus and left inferior frontal gyrus/precentral gyrus) when participants had to remember unfamiliar names (verbal information). In contrast, delay activity was higher in the right hemisphere (right fusiform gyrus, right inferior frontal gyrus, right precentral gyrus, and right medial superior frontal gyrus) when participants had to remember unfamiliar faces (visual information).

1.5 Capacity limits and manipulation costs

Though verbal WM storage and visual WM storage seem to operate independent of one another, both systems exhibit strict limits that constrain their functioning. Factors constraining WM abilities have garnered much attention (Baddeley, 2001), as they may be a locus for broader impacts throughout cognition. In the following sections, I describe the nature of these capacity limits.

1.5.1 Costs associated with storing verbal Information in WM

Chunk-based Limits:

Investigations into the limits of verbal WM storage have typically used span tasks to determine the maximum amount of information that can be maintained in a given moment. In these tasks, verbal stimuli (i.e. digits, letters, words) are presented serially. After a brief delay, participants must recall the stimuli in this same order. The number of items in the series increases until participants are unable to correctly recall the stimuli in the correct order. The set size prior to the onset of recall errors is thought to represent storage capacity.

Investigations of verbal WM storage capacity have yielded conflicting results, as some studies suggesting that individuals can store between 5-8 items of verbal information (Brener, 1940; Miller, 1956), whereas others estimate a lower limit of 3-4 items (Broadbent, 1975; Cowan, 2001). Such inconsistencies may stem from strategies to overcome storage limitations by reorganizing to-be-remembered information into superordinate groups or “chunks” (Gilchrist, Cowan, & Naveh-Benjamin, 2008; Miller, 1956). For example, in a free recall experiment conducted by Tulving and Patkau (1962), participants were asked to memorize and recall a series of words that approximated English syntax to varying degrees. The amount of information that they were able to recall increased as a function of how syntactically close these words were to English grammar. Similar results have been observed in digit span tasks (Ericsson et al. 1980, 2004), where participants were able to reorganize sequences of digits in a meaningful way as a means of remembering more digits (e.g. remembering the sequence 3-5-9 as 3:59 - the amount of time it took Roger Bannister to break the 4 minute mile).

The ability to reorganize verbal information based on semantic meanings has implicated an easy connection between long-term memory and working memory. Such observations have given rise to speculation that representations in verbal WM are merely activations of representations stored in long-term memory, and that the mechanism responsible for such LTM selection is capacity limited [Cowan, 2001; but see Section 1.3.1 for evidence demonstrating independence between WM and LTM).

Temporal Decay and Articulatory Rehearsal:

In contrast, decay theories of verbal WM storage argue that storage capacity is not limited by a set number of chunks. Rather, such theories posit that memory traces passively decay over time (Barrouillet, Bernardin, & Camos, 2004; Towse & Hitch, 1995). Evidence for this theory was initially provided by Baddeley, Thomson, and Buchanan (1975), who observed superior performance for strings of monosyllabic words compared to strings of polysyllabic words. Given that Baddeley and colleagues controlled for the total number of words presented in each string, they concluded that verbal storage capacity was affected by temporal factors.

In the same study, Baddeley and colleagues found that the number of words that participants could articulate out loud within two seconds was predictive of their verbal memory capacity. These findings have been interpreted as suggesting that the amount of information that can be stored in verbal WM is dependent on subvocal articulatory rehearsal processes that protect stored representations from temporal decay (Baddeley & Wilson, 1985; Caplan, Rochon, & Waters, 1992; Della Sala, Logie, Marchetti, & Wynn, 1991). Such interpretations have been supported by experiments using complex span tasks (Barouillet et al., 2007), wherein the recall of verbal information was shown to decrease as a function of the extent to which a secondary task impedes articulatory rehearsal processes.

Interference Theories:

Interference theories have posed the greatest source of opposition to decay theories, primarily because it is difficult to decipher whether impaired memory span performance is attributable to the passage of time or to interference between events that have transpired during that time. For example, in a classic study conducted by Peterson and Peterson (1959), participants were instructed to remember three letters while counting backwards by threes. As expected, memory recall worsened across various delays up to 18 seconds. Though this decrease in memory ability can be attributed to temporal decay, it also may have resulted from interference by the secondary digit task.

Similarly, proactive interference *within* a single task may also have lead to performance decrements across time. In fact, Keppel and Underwood (1962) conducted a study similar to Peterson and Peterson (1959), and found that recall accuracy declines as a function of the number of trials. Moreover, they found that the temporal duration of the retention interval had no effect on memory recall for the very first trial. Given that there are no trials preceding the first trial, proactive interference could not have affected memory accuracy. In this connection, Loess and Waugh (1967), Kincaid and Wickens (1970), and Scheirer and Voss (1969) conducted independent investigations of verbal storage capacity, where they attempted to reduce proactive interference by varying either the intervals or the amount of time elapsed between a target item and a preceding item. In so doing, they found little to no decrement in memory performance across time. Upper limits set on verbal WM storage abilities may therefore depend on the ability to resolve proactive interference (Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999).

1.5.2 Costs associated with manipulating verbal information in WM

Within the context of WM, "manipulations" refers to the execution of computations through which stored information is reorganized or updated in some way (Veltman, Rombouts, & Dolan, 2003). These computations, however, do not come without costs.

Updating quantity information in verbal working memory has been shown to produce costs in response times. In a study conducted by Garavan (1998), triangles and rectangles were presented in a random serial order on screen, and participants were instructed to keep a running tally of the number of exemplars presented for each shape category. To measure updating behavior, participants were able to control the onset of each shape stimulus. Garavan (1998) found that response times to initiate a subsequent onset were shorter when the same shape was presented sequentially, compared to when two different shapes were presented one after another. Similar costs have been observed in studies focusing on arithmetic operations (Oberauer, 2002; Oberauer & Bialkova, 2009), and have demonstrated increase activation of the dorsolateral prefrontal cortex (DLPFC) during updating (Sylvester et al., 2003).

Manipulation costs may also manifest as decrements in memory accuracy that increase as a function of the number of computations performed. For example, in n-back tasks, participants are serially shown a series of letters and must respond when a letter displayed on the screen matches the identity of one displayed "*n*" presentations before. To successfully compare an item of interest to a previously displayed item, participants must continuously update the contents of WM by dropping out items that were displayed more than *n* presentations ago. In this task, manipulation costs are operationalized by performance accuracy, and have been shown to parametrically decrease as a function of manipulation load (Jonides et al., 1997). Such reorganization of information has also been associated with increased activation in the DLPFC (Braver et al., 1997; Jonides et al., 1997; Veltman, Rombouts, & Dolan, 2003).

Independence between verbal storage and verbal manipulation abilities:

To what extent are verbal WM storage and manipulation abilities (in)dependent? Morris and Jones (1990) were among the first to address this question. In their study, participants were presented with memory sequences consisting of four or more letters. Participants were instructed to remember the four most recent digits in a given series. In so doing, they were required to store and to manipulate these contents by dropping the oldest items from the array and adding the most recent one. Morris and Jones (1990) observed a cost in accuracy for manipulating information, as performance was worse when participants had to update the contents of the list, compared to when no update was required (participants only presented with 4 letters across entire trial).

To determine whether verbal WM storage and manipulation are independent of one another, participants were also given a concurrent articulatory suppression task that was known to disrupt verbal storage ability (Baddeley & Hitch, 1974; Baddeley, Lewis, & Vallar, 1984). If storage and manipulation processes shared a common resource, the ability to manipulate information in this task would be expected to be worse, compared to when no articulatory suppression is enforced – because previous work had demonstrated that articulatory suppression disrupted storage (for review, see Baddeley, 1986). However, this was not the case, as Morris and Jones (1990) failed to find an interaction between performance accuracy and the presence or absence of articulatory suppression. This finding was interpreted as support for independence between storage and manipulation abilities in verbal WM.

The argument of independence between storage and manipulation abilities is also supported by neurological evidence. D'Esposito and colleagues (1999) demonstrated a functional organization of the prefrontal cortex (PFC) based on storage and manipulation processes intrinsic to verbal WM. Participants completed an event-related fMRI delayed-response task in which they were instructed to either store a sequence of letters across a delay period, or to manipulate the sequence by alphabetizing the array. D'Esposito and colleagues found that DLPFC and ventrolateral prefrontal cortex (VLPFC) were activated for both conditions, but DLPFC activation was higher under manipulation conditions. Postle, Berger, and D'Esposito (1999) extended these findings to demonstrate an anatomical dissociation of the prefrontal cortex. They had participants complete a similar alphabetization task and varied both manipulation load (reorder five randomly ordered letters vs. do not reorder letters (i.e., already in alphabetical order)) and storage load (remember either 2 items or 5 items). In so doing, they observed a double dissociation, such that DLPFC demonstrated sensitivity to manipulation but not storage load, whereas VLPFC demonstrated the opposite pattern of activation.

Taken together, evidence from behavioral and neurological investigations of verbal WM have been interpreted as demonstrating independence between storage and manipulation processes in this system.

1.5.3 Costs associated with storing visual information in WM

Factors underlying apparent storage costs in visual WM remains an active area of debate (Suchow et al., 2014). Investigations into this topic have spurred various theories focusing on the existence of an upper bound for storage capacity, the format of stored representations, and the flexibility of this system. Despite differences among these theories, they can largely be separated into two general categories: discrete slots models and continuous resource models. In the following sections, I provide overviews of these models, and describe evidence supporting and opposing their respective frameworks.

Discrete Slots Model:

At its core, the discrete slot model conceptualizes visual WM storage as (1) limited by an upper bound that is (2) determined by a discrete number of (3) integrated object representations.

This model developed from a seminal study conducted by Luck & Vogel (1997), who used a variant of Phillips' (1988) static change detection task to quantify visual WM storage capacity. In this task, participants were instructed to remember an array consisting of a varying set size of objects defined by suprathreshold features (e.g. color, orientation, etc.). These objects were presented simultaneously for 100 ms. After a blank consolidation display of 900 ms, a test array was presented that was either identical to the memory array or differed on the basis of a single feature. Participants were asked to make a two-alternative forced choice, indicating whether the two arrays were identical or differed in some respect (high threshold response of "change" or "no change"). To prevent contamination from verbal working memory, participants were instructed to subvocally rehearse two digits throughout each trial.

Successful completion of the static change detection required observers to compare the representations of items stored in memory (subject to a visual WM storage limit) with the items that were currently attended and available for free viewing. As such, resultant performance accuracies are thought to reflect the maximum number of individual items or amount of visual information that can be stored in visual WM to the total number of items presented in the display, *N*. These accuracy rates can then be transformed into estimates of visual WM storage capacity, *K,* using Pashler's (1988) equation (Proportion Correct = K/N).

Through a series of experiments, Luck and Vogel (1997) had participants complete static change detection tasks, in which the number of objects presented in the memory array varied across trials (e.g. 1-12 colored squares). Most critically, they found performance to asymptote at 3-4 items, after which accuracy dropped precipitously as a function of set size. This limit was also reflected in individual differences in visual WM storage capacity, as the average K value among participants centered on 3-4 items. This pattern of results remained unaffected by the presence or absence of a verbal load, suggesting that this asymptote strictly reflect limits in *visual* WM. Furthermore, accuracy was shown to consistently asymptote at 3-4 items, regardless of whether the consolidation interval was extended up to 4900 ms, ruling out possible effects associated with temporal delay (e.g. decay). The results of these experiments provided the foundation for the Discrete Slots model of visual WM (colloquially referred to as the Fixed Slots model), which posits that only 3-4 representations can be stored within the system at a given moment. Subsequent evidence demonstrates that this limit is specific to the number of objects stored in memory and not the number of spatial locations (Lee

&, Chun, 2001),

The Discrete Slots model differ from competing classes of theories primarily based on their conceptualization of visual WM as limited by integrated object representations, as opposed to individual features. This hypothesis was initially based on object-based theories of attention (Duncan, 1984; Egly, Driver, & Rafal, 1994; Kahneman, Treisman, & Gibbs, 1992; Vecera & Farah, 1994), which propose that selective attention focuses on integrated object representations and not individual features. Given that selective attention provides the input that constitutes the contents of visual WM, it is plausible for the format of visual WM representations to be integrated objects.

To demonstrate that visual WM storage capacity is limited by integrated objects, Luck and Vogel (1997) presented participants with a static change detection task in which they varied the visual complexity of the stimuli. Instead of presenting memory arrays that solely consisted of stimuli defined by a single feature (e.g. colored squares or black lines of varying orientations), they also had a separate condition where they presented stimuli that were defined by a conjunction of features (e.g. lines that varied in both orientation and in color). If visual WM storage is limited by individual features, performance in the conjunction condition should be lower than that in the single-feature condition, suggesting that multifeature objects consume more real estate in visual WM. Additionally, accuracy rates should asymptote earlier than set size 4, the plateau observed for single-feature displays. In contrast, if visual WM storage is limited by integrated objects, performance in the conjunction condition should be equivalent to the single-feature condition, and both should asymptote at set size 4.

Luck and Vogel (1997) found the latter to be the case. This was true regardless of whether the stimulus conjunctions were defined by (1) color and orientation and (2) color, orientation, size, and presence/absence of a gap. Additionally, this pattern of results replicated even when the stimuli were comprised of (3) color-color conjunctions (e.g. a blue square within a pink square), suggesting that features of conjunction items are not stored in independent storage systems (i.e. there is no store for orientation information that is independent of one for color). Taken together, the results of Luck and Vogel's (1997) study provided the foundation for discrete slots models, which conceptualize visual WM storage capacity as limited to 3-4 object representations.

Opposition to the Discrete Slots Model:

The advent of the Discrete Slots model gave rise to a wave of research attempting to further characterize visual WM storage capacity. Subsequent studies provided evidence supporting this theory using various approaches, including neurophysiological (Ikkai, McCollough, & Vogel, 2010; Vogel & Machizawa, 2004) and neuroimaging (Todd & Marois, 2004; Xu & Chun, 2006) methodologies.

In contrast, a series of investigations yielded results that conflict with the central tenets of the Discrete Slots Model. These studies primarily either failed to replicate findings that provided the foundation for these models (Delvenne & Bruyer, 2004; Olson & Jiang, 2002; Wheeler & Treisman, 2002; Xu, 2002; Xu, 2006) or produced results that were incompatible with these theories (Alvarez & Cavanagh, 2004; Fougnie, Asplund, & Marois, 2011; Olsson & Poom, 2005).

Wheeler and Treisman (2002) were of the first to publish work demonstrating a failure to replicate Luck and Vogel's (1997) critical conjunction experiments. In their study, Wheeler and Treisman presented participants with a static change detection task, in which the memory arrays consisted of either three bicolored squares (color-color conjunction) or six squares that each had a single color (single-feature). They found performance accuracy to be higher in the single-feature condition compared to the conjunction condition, suggesting that visual WM storage capacity is limited by the total number of features present (and not by the total number of integrated objects).

Olson and Jiang (2002) also failed to replicate Luck and Vogel's (1997) bicolored conjunction condition. However, within the conjunction conditions, they additionally varied the saturation of colors and found that performance was better when the stimuli consisted of high-saturation colors compared to low-saturation colors (though performance in the single-feature condition was always higher than high or low saturation conjunction conditions). This led Olson and Jiang to suggest that the results observed in Luck and Vogel's (1997) experiment was stimulus-specific, such that the latter researchers' use of high-contrast colors drove participants to remember color contrast cues. They argued that participants would not have to remember 2 individual colors per item, but rather, would only have to remember one contrast relation. This would manifest as equivalent behavioral performance across conjunction and single-feature conditions.

In contrast to studies that failed to replicate the results of Luck and Vogel's (1997) conjunction experiments (e.g. Wheeler & Treisman, 2002; Olson & Jiang, 2002), Fougnie, Asplund, and Marois (2010) demonstrated that there is indeed no cost for maintaining multiple features of an object in visual WM. In their study, participants completed a static change detection task, in which the memory array consisted of triangles that varied in orientation (1 to 360 degrees) and color (chosen from a continuous color wheel consisting of 1 to 360 possible colors). They were instructed to either remember the orientation, the color, or both the orientation and color of the memory items. Whereas Luck and Vogel (1997) had participants make a two-alternative forced choice to respond whether the memory and test arrays were identical or not, Fougnie and colleagues used a continuous report method (click on exact value from all 1 to 360 possible values) so that participants would be able to report the exact identity (color or orientation) of a cued item. This response method provided a way to measure both the probability that the cued item was stored in memory (Pmem) and the precision with which that item was represented (σ). Fougnie and colleagues (2011) failed to find differences between the single-feature and conjunction conditions in the probability that a cued item was stored in memory (consistent with Luck & Vogel, 1997). However, significant differences were observed in the fidelity of these representations, such that items were less precisely represented in visual WM in the conjunction condition, compared to the single-feature condition. These results provide evidence against discrete slots models, which claim that increases in object features do not produce storage costs in visual WM. Furthermore, these results argue against claims that individual feature stores exist that maintain information about different feature dimensions and have independent capacity limits (Wheeler & Treisman, 2002).

It remains unclear whether visual stimuli are stored as integrated objects, independent features, or some combination of the two. However, empirical results that fail to support the central tenets of Discrete Slots Models have given rise to alternative theories that aim to characterize limits in visual WM storage.

Continuous Resource Models:

At their core, Continuous Resource models conceptualize visual WM storage abilities as limited by a (1) finite commodity that can be (2) continuously divided among and (3) flexibly allocated to (4) both features and objects (Suchow et al., 2014). However, distinct differences exist among models that are grouped under this class category. Here, I provide an overview of two specific models, the Bounded-Resource Limited Model (Alvarez & Cavanagh, 2004) and the Unbounded-Resource Limited Model (Bays & Husain, 2008; Wilken & Ma, 2004), and provide evidence supporting these theories.

<u>*Bounded-Resource Limited Model (colloquially referred to as the Flexible Slots Model):*</u>

The Bounded-Resource Limited model promotes a middle ground between Discrete Slots models (that argue for a 4-item limit of visual WM storage capacity) and strict Continuous Resource models (that reject the notion of a fixed upper bound). According to this theory, visual WM storage capacity is information-limited (where information load varies due to object features), but is still held to a maximum of four representations.

This model is based on work conducted by Alvarez and Cavanagh (2004), who manipulated the overall information load of objects presented in a static change detection task. In this study, participants were shown a memory array that consisted of items belonging to a particular category (colored squares, letters, polygons, Snodgrass drawings, Kanji characters, shaded cubes). These items varied in information load, as operationalized by processing rates observed in a separate visual search task. After the memory array was presented and was followed by a brief consolidation display, a test array was presented that was either identical to the memory array or nearly identical such that one item had changed identity (always a within-category change). Participants were instructed to make a two-alternative forced choice (2AFC) response (same or different), which was used to calculate estimates of visual WM storage capacity, K, using Pashler's (1988) equation.

This design allowed for the evaluation of two main hypotheses. If visual WM storage capacity is limited by the maximum number of object representations, K estimates should be equivalent across all stimulus categories. In contrast, if visual WM storage capacity is limited by information load, these estimates should vary across the stimulus categories. Alvarez & Cavanagh (2004) found the latter to be true. They observed an inverse relationship between estimates of storage capacity and information load, providing evidence against Discrete Slot models. However, consistent with Discrete Slot models, participants were able to remember up to a maximum of 4 colored squares. Taken together, these results provided the foundation for the Bounded-Resource model, which conceptualizes limits in visual WM storage as limited by information load (informationally complex items take up more real estate in visual WM) and limited to a maximum number of 4 representations.

Such an information-theoretic model of visual WM is supported by evidence demonstrating that information stored in memory can be compressed, providing a means to overcome limitations in storage capacity. Brady, Konkle, and Alvarez (2009) presented participants with a static change detection task, in which memory arrays consisted of four items, wherein each item consisted of a small circle embedded within a larger circle. The colors of the circles were chosen randomly without replacement, such that participants had to maintain eight color values in visual WM (exceeding the four item limit). Brady and colleagues also manipulated the probability with which pairs of colors would co-occur within a single item (i.e. a smaller blue circle is presented within a larger red circle on 80% of trials). In so doing, they found that capacity estimates increased across the testing period. These results oppose item-based models of visual WM, which would predict that capacity estimates would be equivalent (i.e. if you are presented with four concentric circles and storage capacity is limited to four integrated objects, your K value should always equal four items). Brady and colleagues (2009) interpreted their findings as indicative of participants' abilities to extract statistical regularities and compress representations of high probability pairs into more efficient representations, thus, allowing for more items to be stored in memory.

Opposition to Bounded-Resource Limited Model:

Opposition to the Bounded-Resource Limited model are rooted in the claim that the information-based costs observed in Alvarez and Cavanagh's (2004) study resulted from an increase in comparison errors made during the decision-making phase, and *not* from storage limitations. According to this argument, items that have higher information loads (e.g. a Kanji character compared to a colored square) will have higher memory-test array similarity. This increases the number of feature comparisons that are needed to make a change detection decision, and will resultantly increase the probability of making a comparison error. Awh, Barton, and Vogel (2008) tested this hypothesis by having participants complete a static change detection task similar to Alvarez and Cavanagh's (2004) study, but with one key difference: instead of having changes across memory and test displays be within-category changes (e.g. a shaded cube changing into another shaded cube), these changes could be cross-categories (e.g. a shaded cube changing into a colored square). If items with higher informational loads occupy more space in visual WM, estimates of storage capacity should vary across categories for both within- and between-category changes. Awh and colleagues (2008) failed to observe these results. They replicated Alvarez and Cavanagh's (2004) results only for the within-category condition. Capacity estimates did not vary across stimulus categories when the changes between memory and test arrays were between-category changes. Moreover, participants were able to remember approximately 4 items for all stimulus categories for these between-category changes.

The results observed by Awh and colleagues (2008) have been criticized, in turn. Specifically, performance accuracy in the between-category change condition may have been inflated, since participants did not have to store visual information in memory if they were strictly used categorical information to guide their comparisons (e.g. cube turned to colored square). Furthermore, given that between-category changes exhibit large differences in textural and spatial features across the memory and test displays (e.g. a cluster of cubes that are dark and turning into a group with one Kanji character that is not dark), change detection accuracy may have been inflated via ensemble processing. In fact, when the ability to use ensemble representations in between-category change conditions is controlled for, individuals can remember approximately 1-2 objects (Brady & Alvarez, 2015).

Unbounded-Resource Limited Model

Similar to Bounded-Resource Limited models, *Un*bounded-Resource Limited models conceptualize visual WM storage capacity as information-based and limited by a finite resource. However, these theories reject the argument that visual WM storage is bounded by a maximum number of representations. Rather, they suggest that visual WM storage is supported by a finite resource that can be continuously divided among representations (Bays & Husain, 2008; van den Berg et al., 2012; Wilken & Ma, 2004). Accordingly, the fidelity of stored representations varies based on how much resource is allocated to each representation. The division of this resource will be determined by the overall information load of the to-be-remembered array (this can vary by the set size or featural complexity of items) and top-down goals.

Wilken and Ma (2004) laid the foundation for the Unbounded-Resource Limited model by providing evidence that contradicts fundamental assumptions underlying high-threshold models (e.g. Discrete Slots and Bounded-Resource Limited models). These models assume that (1) each item/piece of featural information is represented in an "all-or-none" fashion (without internal noise) in visual WM. Furthermore, (2) they assume that change-detection responses are always based on the presence or absence of the target item, and fail to consider the possibility of decisions being made based on non-target items (correspondence errors). Throughout a series of 2AFC change detection tasks, Wilken and Ma (2004) challenged these assumptions by comparing theoretical predictions of high-threshold models to predictions of a signal-detection model that accounts for noisy representations and correspondence errors. In all cases, the second model provided a better fit to the behavioral data exhibited by human participants.

Additionally, Wilken and Ma (2004) developed the continuous report method, which has become the hallmark method for measuring the fidelity of representations stored in visual WM. This paradigm is similar to static change detection tasks, with the following exceptions. First, featural information of to-be-remembered items are not chosen from a set of discrete values. Rather, they are selected from a set of continuous values drawn from a circular featural dimension. Second, unlike static change detection tasks, an array of items is not shown during the test phase and participants do not have to make a 2AFC response as to whether these items were identical to those presented in the memory array. Rather, placeholders are typically presented in the locations of previously occupied items. All possible feature values are then presented (e.g. using a color wheel), and participants must report the exact identity of a target item, (indicated by a cue presented at its corresponding location) by clicking on a single value. If the cued representation is stored in visual WM, the magnitude of this difference should be relatively small and be normally distributed (across trials). The fidelity of the cued representation (precision) is operationalized as the inverse of the standard deviation of this distribution.

Wilken and Ma (2004) used the continuous report method to demonstrate that the precision with which items are represented in visual WM decreases as a function of memory set size. These results gave rise to the Unbounded-Resource Limited model, which claims that visual WM is *not* limited by a fixed number of representations. Rather, the "four-item" limit hailed by Discrete Slot and Bounded-Resource Limited models is simply a behavioral artifact. Individuals can store an unbounded amount of information in visual WM, but the precision with which the information-per-individual is represented will vary with total information load. When memory set sizes exceed 4 items, individuals may store more than four items in memory, but the storage resource will be distributed thinly. Therefore, the information stored in visual WM may no longer be represented with the appropriate amount of precision that is required to make successful comparisons. This can give rise to errors in change detection and give the *appearance* of a 4-item limit.

The Unbounded-Resource Limited model is supported by studies demonstrating the rapid redistribution of this continuous resource amongst items via attentional control. For example, Bays and Husain (2008) had participants complete continuous report tasks, in which they were instructed to identify the orientation of a target item. However, during the blank display that was interleaved between the memory and test phases, participants' attention was either maintained at fixation or was oriented towards the location of a previously occupied item. Consistent in both maintain and shift attention conditions, the fidelity of representations declined as a function of set size. However, in the shift attention condition, the item to which participants made a saccade was represented with higher fidelity compared to the non-saccade item. Similarly, in a separate experiment, they had participants sequentially saccade to five locations previously occupied by memory items, and found that the item presented last in the series was always represented with the highest level of precision. Taken together, Bays and Husain interpreted this as evidence for a preferential redistribution of a highly flexible and continuous visual WM resource.

<u>Opposition to Unbounded-Resource Limited Model:</u>

The Unbounded-Resource Limited model initially received opposition due to criticisms of Wilken and Ma's (2004) interpretation of results. Wilken and Ma did not account for the possibility that, on supracapacity trials, the cued representation may not be stored in visual WM. On these trials, participants will guess randomly, and the distribution of errors between the reported and actual feature values will be uniformly distributed. Therefore, participants may be able to represent up to 4-items with fixed precision and randomly guess when set sizes exceed this limit (giving the appearance of variability in precision as a function of set size). This account is in accordance with the Discrete Slots Model of visual WM.

In their study, Zhang and Luck (2008) also found that precision did vary across all set sizes. To account for these results, Discrete Slot models evolved to include an additional aspect. Namely, theorists suggest that, although limits exist in the number of representations that can be stored in visual WM and how precisely they are represented, the factors constraining these limits are independent of one another (Anderson, Vogel, & Awh, 2011; Barton, Ester, & Awh, 2008; Zhang & Luck, 2008). For example, based on their findings, Zhang and Luck (2008) developed the Slots and Averaging model. This theory suggests that there are a fixed number of slots available in memory, and a single item can be represented using all slots. However, as set size increases, fewer slots would be available to represent a single item. The number of slots used, therefore, corresponds to the precision of that representation, which is the average of the representation of the object across the number of slots that it is held in.

1.6 Outline of dissertation

Investigating constraints placed on working memory has proven advantageous for conceptualizing the architecture of this system. Costs associated with storing information in the system have been used to demonstrate dissociations between working memory vs. long-term and iconic memory. Furthermore, such costs have been used to establish domain specificity within the system itself. However, relatively less emphasis has been placed on exploring constraints on manipulation ability, as opposed those in storage. For this reason, the current dissertation focuses on investigating costs associated with manipulating information in visual working memory, and determining how these costs interact with those for storing information in the system.

In Chapter 2, I present a novel paradigm that I use to demonstrate costs associated with manipulating visual information. In Chapter 3, I investigate how these costs affect these for storing information. I then investigate the compliment of this relationship by examining whether costs in storage interact with those for manipulating information, in Chapter 4. Lastly, in Chapter 5, I summarize these experiments by presenting a working model that describes what happens when information is manipulated in visual working memory.

Chapter 2: Are there costs associated with manipulating information in Visual Working Memory?

2.1 Overview of Chapter 2

In this chapter, I investigate whether there are costs associated with manipulating information in visual working memory (VWM). To this end, I focus on a specific type of manipulation that we use every day: the ability to update the binding of featural-spatial information as an object undergoes smooth motion. This computation is commonly performed across a variety of settings, ranging from mental rotation in educational settings (e.g. comparison of cis- and trans- isomers in chemistry) to military combat (e.g. tracking battalion members while executing a strategic attack).

To investigate possible costs in visual manipulation ability, I developed a novel paradigm, the dynamic change detection task, which combines attributes of the static change detection task with those of paradigms requiring manipulation computations (Kahneman, Treisman & Gibbs, 1992; Hollingworth & Rasmussen, 2010). In this task, participants are presented with colored circles, whose colors disappear, leaving behind outlines. Pairs of outlines proceed to undergo smooth motion and swap positions, requiring participants to update the featural-spatial binding for that object. Once all swaps are complete, memory for a target item is tested either using a probe method (color appears in one circle, and participants are instructed to respond whether they expected to see that color appear in that circle) or a delayed identification method (participants must report identity of cued item by choosing from a set of options).

As is the case with the static change detection task, I vary the number of items presented in the display, from 2 to 4, to determine costs associated with storing items in this paradigm. Similarly, I vary the number of swaps that take place, from 0 (static condition) up to 4 swaps (dynamic conditions), to determine costs associated with manipulating information in VWM. The interaction of set size and number of manipulations allows for an assessment of the relationship between limits in storage and manipulation abilities in VWM.

If there are no costs associated with manipulating information, accuracy across all dynamic conditions should be equivalent to performance on the static condition, for each set size. This would suggest that performance is solely constrained by storage limitations. However, if there are costs associated with manipulating information, this may manifest in many ways. One possibility includes little to no cost associated with manipulating the smallest set size, whereas systematic decreases in accuracy would be observed as a function of manipulations performed for larger set sizes.

Here, I use the dynamic change detection task to distinguish between these possible patterns of results (Experiments 1a,b). Furthermore, I perform a series of experiments where I control for potential confounding factors, such as durability (Experiments 2a-b), temporal delay (Experiments 3a-b), and interference (Experiments 4a-b), which may affect working memory abilities. In so doing, I determine whether there are costs associated with manipulating information in VWM, and investigate the relationship between these costs with those for storing information in the system (Chapters 3 and 4).

2.2 Experiment 1 - Response Method

The experiments described in Section 2.1 aim to investigate costs associated with manipulating information in VWM. Methodologically, these experiments are identical with the exception of their respective response methods. In Experiment 1a, participants must respond whether they expected to see a probed color appear at a certain location in the test display (probe response method). This response method is akin to those used in traditional static change detection tasks (Alvarez & Cavanagh, 2004; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001). In Experiment 1b, participants must identify the color they expected to see appear at a cued location by choosing from a color bar of possible options (delayed identification method). This modified response method provides the advantage of characterizing the types of errors participants make when manipulating information in VWM. As we will see, both response methods provide similar patterns of results.

2.2.1 Experiment 1a – Probe Response

In Experiment 1a, I used the dynamic change detection task to assess observers' performance with both static and dynamic displays. To ensure that participants were not able to encode and manipulate stimuli verbally, each trial included a two-digit verbal load that participants were instructed to subvocally rehearse throughout the course of the entire trial (Baddeley, 1986; Vogel, Woodman, & Luck, 2001). Indeed, all experiments described throughout this dissertation incorporated a verbal load to prevent the recruitment of verbal strategies.

Participants

Twenty-four Johns Hopkins University students with normal or correct-to-normal vision took part in the study in exchange for course credit.

Equipment

The experiment was conducted in a dimly lit room. Stimuli were presented on a Macintosh iMac computer with a viewable area of 43.5 x 27 cm. Viewing distance was not fixed, but averaged approximately 60 cm.

Stimuli

The verbal load for each trial consisted of two black digits presented at the center of the screen, each measuring 1.7° x 0.85° of visual angle. All memory displays consisted of colored circles (diameter of each circle: 1.23° of visual angle), whose locations were randomly chosen from four vertices of an imaginary square (7.35° x 7.35° of visual angle) that was located at the center of the screen. The colors with which these circles could appear were randomly chosen without replacement from eight discrete categories: red, cyan, yellow, green, blue, orange, brown, and magenta. Each circle was framed by a circular white outline, whose thickness measured 0.13° of visual angle.

Procedure

Participants completed 150 randomly shuffled trials of the dynamic change detection task (Figure 1). The start of each trial was marked by a central fixation cross (black, 0.5° x 0.5° of visual angle) that was presented for 500 ms. After an interstimulus interval of 100 ms, participants were presented with a two-digit verbal load that they were previously instructed to rehearse subvocally throughout the trial. These digits (Font Size: 35, Font: Calibri, Color: white) were presented for 500 ms, and were followed by a memory display, after an interstimulus interval of 1000 ms. Each memory display consisted of a varying set size of colored circles with white outlines. This display was presented for 500 ms, and was followed by a screen in which the colors of the circles disappeared, leaving behind the white outlines. After the colors disappeared, the display remained static for a memory consolidation period lasting 1900 ms. Following this consolidation period, one of two trial types occurred (i.e., static or dynamic).

In the static condition (0 swaps), the consolidation period was immediately succeeded by the presentation of the test display. In this way, the 0 swap trials resembled a typical static change detection task, and performance on 0 swap trials was used to estimate limitations in storage capacity.

In the dynamic conditions, the consolidation period was followed by dynamic displays where two of the circular items (still defined by their white outlines) proceeded to swap positions at a rate of 100 pixels per frame. During each swap, the pair of targets would move smoothly across the screen, following a parabolic trajectory, passing each other, and then come to rest in their new positions. Dynamic trials included 1, 2, 3, or 4 swaps. Each swap lasted an average of 1650 ms, and was separated by a 1600 ms reconsolidation period prior to the onset of the next event (i.e., either the test display or another swap). The selection of which targets would participate in a given swap was random and unconstrained. The observer's task was to watch the swap and attempt to update their representations of where each color would appear in the test display. Thus, performance on dynamic trials was used to estimate the observer's ability to dynamically update visuo-spatial information in VWM.

After all swaps and consolidation periods were completed, participants were presented with the test display. In both static and dynamic conditions, the white outlines turned black for 500 ms to signal the onset of the test display. These circular outlines then turned white once more and one item filled with a color that was presented in the initial memory display. On half of all trials, this probed color appeared in the correct location – given the swaps that had occurred. On the remaining half of trials, the probe color was incorrect (appearing in the wrong location). On incorrect dynamic trials, the incorrect probe color was constrained to appear on an item that had participated in at least one swap; on incorrect static trials (0 swap), the incorrect probe color was allowed to appear at any of the incorrect locations in the test display. Participants were instructed to respond whether the probe color in the test array appeared in the correct position given the movements they observed. Following their response, participants used the keyboard to type in the to-be-remembered digits that were presented at the beginning of that trial.

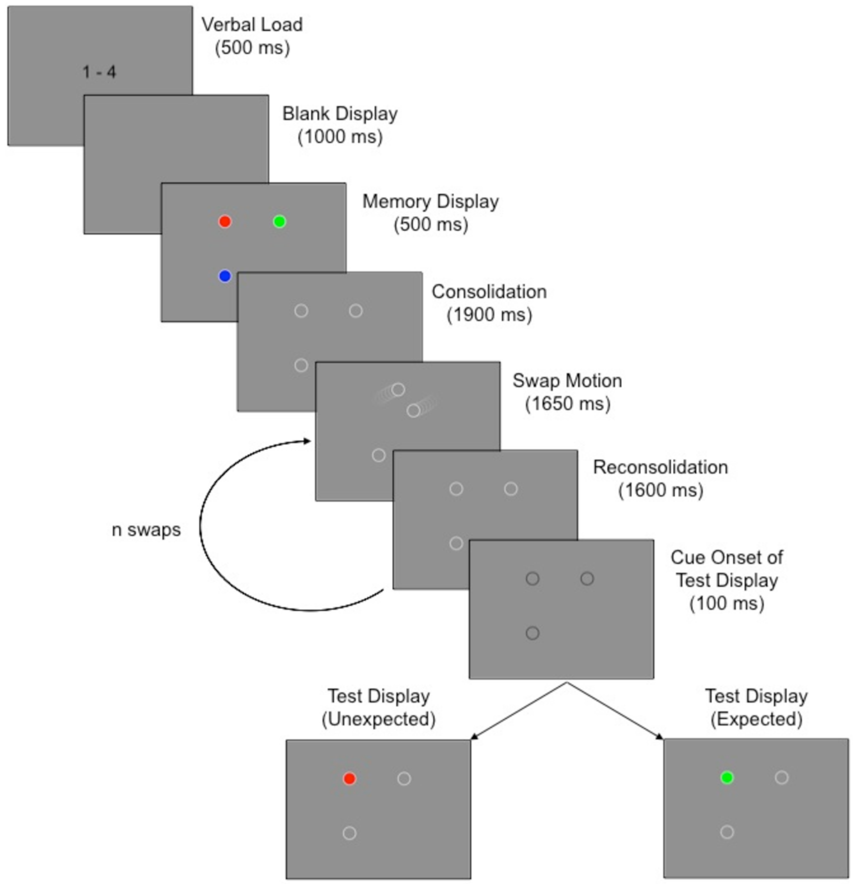


***Figure 1*. Schematic of dynamic change detection task (with probe response) used in Experiment 1a.**

Results:

The results of Experiment 1a are illustrated in Figure 2. The overall pattern of results based on change detection accuracy remain the same regardless of whether analyses were performed strictly on trials where participants correctly reported the verbal load or on all trials. Here, I describe the analyses performed on change detection accuracy for trials where participants correctly reported the verbal load.

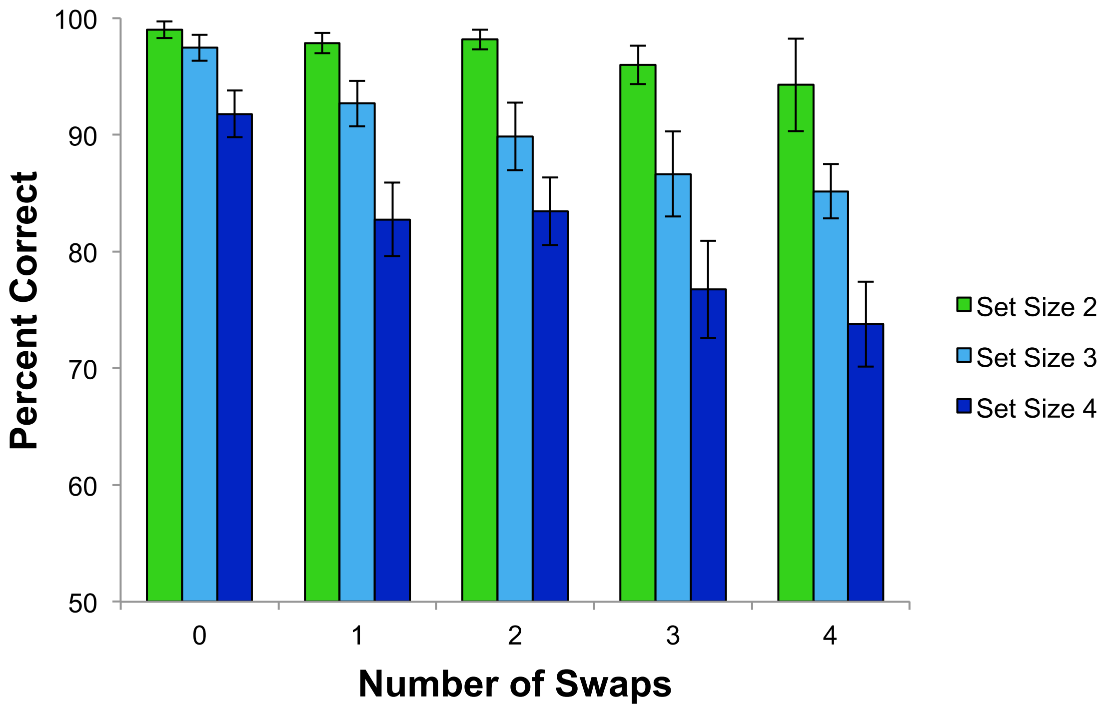


Figure 2**. Results (percent correct) observed in Experiment 1a - dynamic change detection task with probe response method. Whereas, little-to-no cost is observed for manipulating 2 items, manipulating 3 or 4 items results in performance decrements that increase as a function of the number of swaps.**

A 3 (set size) x 5 (number of swaps) within-subjects ANOVA revealed a significant main effect of set size, $F(2,46)=40.09$, $p<.001$, $\eta_p^2=.64$. Performance was highest for set size 2, which differed from both set size 3, $F(1,46)=28.98$, $p<.05$, and set size 4, $F(1,46)=61.29$, $p<.05$. Performance for set size 3 was also significantly better than set size 4, $F(1,46)=21.24$, $p<.05$. Furthermore, the ANOVA revealed a significant main effect of number of swaps $F(4,92)=10.11$, $p<.001$, $\eta_p^2=.31$, as performance decreased with increasing numbers of swaps. Specifically, performance was higher in the static (0 swaps) condition compared to the dynamic (1-4 swaps) conditions, $F(1,92)=34.84$, $p<.05$, suggesting that there is an increased cost associated with manipulating representations, relative to simply storing them in visual WM.

Interestingly, the ANOVA revealed a significant interaction of set size x number of swaps, $F(8,184)=2.64$, $p<.03$, $\eta_p^2=.10$ (Figure 2). A significant linear (set size 2) x linear (set sizes 3 and 4) contrast was observed, $F(1,184)=22.79$, $p<.05$, suggesting differential effects for manipulating 2 items in visual WM, compared to manipulating 3 or 4. Taken together, these results demonstrate little to no cost for manipulating 2 items, whereas performance systematically decreases as a function of the number of swaps when manipulating 3 or 4.

2.2.2 Experiment 1b – Delayed Identification Response Method

Though the results of Experiment 1a provide evidence for costs associated with manipulating information in VWM, the differential effects observed based on set size may have resulted from differences in encoding strategies. Specifically, given that only one item was probed in the test display, participants may have selectively encoded only N-1 items in each condition. This strategy may behaviorally manifest as little-to-no costs for set size 2 trials, since participants may have updated the spatial-feature information of one item and used this information to infer the identity of the other.

To disrupt the use of this selective strategy, in Experiment 1b I altered the response method used. In Experiment 1b, the target item in the test display was cued by a black square outline and participants were instructed to click on the correct color for that object from an option bar that presented all possible color values. This delayed identification response method deters participants from adopting an N-1 memory strategy (e.g., because one must retain color information for each object), and additionally, provides insight into the type of incorrect responses that are made in this task (e.g., substituting an initially presented color for the target).

Methods:

Thirteen participants completed 300 trials of a dynamic change detection task identical to that used in Experiment 1a, with the following exceptions. First, participants were asked to vocally rehearse the two-digit verbal load aloud throughout the entire duration of the trial (as opposed to subvocally) and were not asked to report the identity of the digits at the end of each trial. Second, as already mentioned, the method with which participants indicated the identity of the target stimulus was changed. Whereas in the previous experiment one outline was filled in with a probed color in the test display, in Experiment 1b, the target stimulus was indicated by a black square outline (2.45° by 2.45° of visual angle). Participants had to indicate the identity of that stimulus by using the mouse to click on a color that appeared in a color bar. The color bar was always comprised of 8 squares that were arranged horizontally and contained all of the possible discrete colors used in the memory display (Figure 3). This method provides the additional advantage of characterizing the types of errors participants make in this task (reporting the identity of a color presented in the memory display vs. one that was not shown at all). More importantly, by changing the response mode in this way, participants were encouraged to encode the identities of all items presented in the memory display.

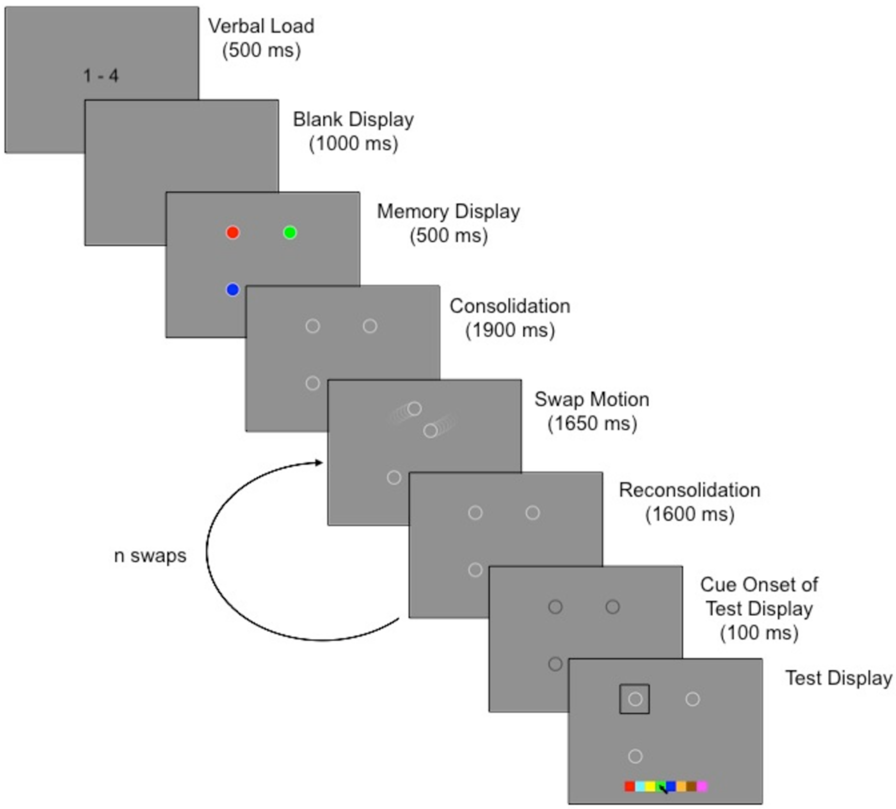


***Figure 3*. Schematic of dynamic change detection task (with delayed identification response) used in Experiment 1b. During the test phase, participants were instructed to report the identity of a cued item by clicking on an option bar.**

Results:

Changing the response mode did not produce differences in the pattern of correct responses compared to those observed in the previous experiment (Figure 4). A 3 (set size) x 5 (number of swaps) within-subjects ANOVA yielded a significant main effect of set size, $F(2,24)=120.44$, $p<.001$, $\eta_p^2=.91$. Participants were most accurate for set size 2 conditions, compared to set size 3, $F(1,24)=44.64$, $p<.05$, and set size 4, $F(1,24)=149.05$, $p<.05$, conditions. Performance on set size 3 was also higher than performance on set size 4, $F(1,24)=140.56$, $p<.05$. Furthermore, a significant main effect of number of swaps was observed, $F(4,48)=30.42$, $p<.001$, $\eta_p^2=.72$, where performance was higher on the static compared to the dynamic conditions, $F(1,48)=113.20$, $p<.05$. Once more, the ANOVA yielded a significant interaction of set size x number of swaps, $F(8,96)=3.00$ $p<.03$, $\eta_p^2=.20$. Whereas accuracy for set size 2 across all conditions remained relatively steady, performance for set sizes 3 and 4 decreased as a function of the number of swaps performed, $F(1,96)=19.94$, $p<.05$.

As in Experiment 1a, I this pattern suggests that participants experienced very little cost for manipulating 2 items in VWM and experienced growing costs for set sizes 3 and 4 as the number of swaps increased.

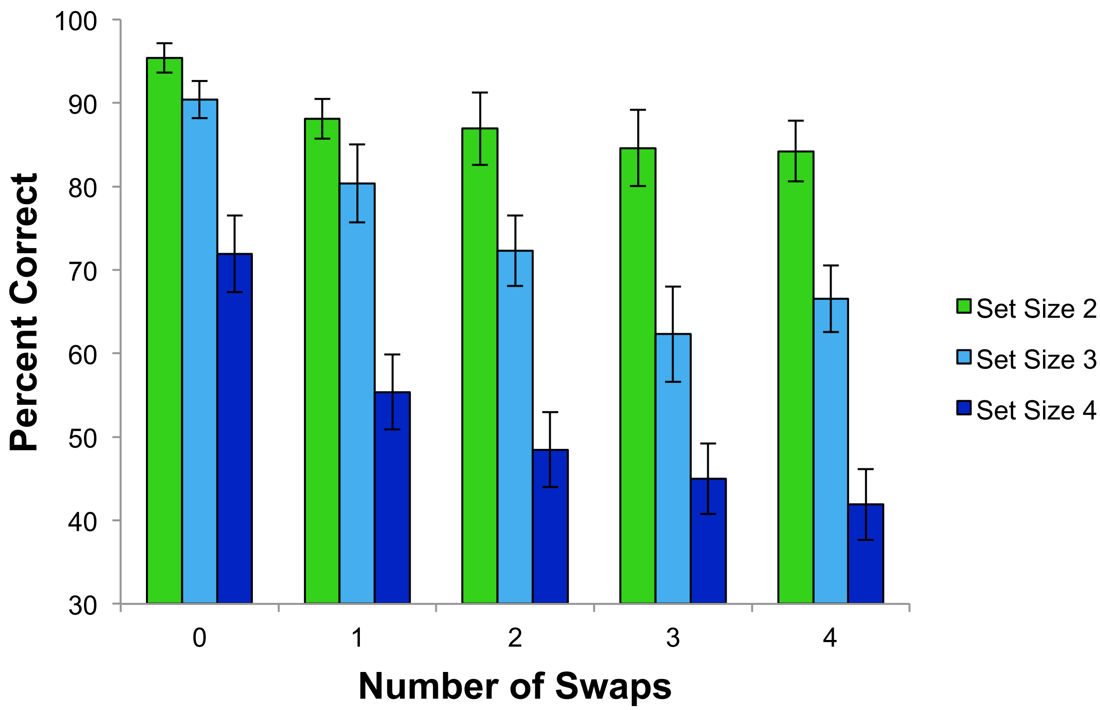


Figure 4. **Results (percent correct) observed in Experiment 1b - dynamic change detection task with delayed identification response method). Once more, a disparity was observed in manipulation ability for displays consisting of 2 vs. 3 or 4 items.**

Incorrect responses observed in the dynamic change detection task can largely be classified into two categories. First, participants can make "non-target confusions", where they incorrectly report the identity of an item that was presented in the memory display but was not the cued target. These errors may stem from a failure to successfully update featural-spatial information, during a given swap. Second, participant can also make "random guesses", where they incorrectly identify a color that was not presented in the initial memory display. These guesses may result from items being dropped out of VWM during the updating process or during lapses of attention, or from incomplete encoding of the memory display. Across all set sizes, participants made non-target confusion errors on 59% of all incorrect trials. The proportion of these errors for set size 2 ($M_{weighted}$=55.90%) and set size 3 ($M_{weighted}$=54.47%) were lower compared to set size 4 ($M_{weighted}$=65.30%); and each of these exceeded the error rates expected by chance for random guessing for these set sizes (i.e., if observers clicked randomly, non-target confusion errors would be expected to account for 29%, 43%, and 57% of incorrect trials respectively). This suggests that observers make a high rate of non-target confusion errors for set size 2 (compared to the chance level), and that non-target confusion errors remain high (but somewhat diminished) for set sizes 3 and 4 (compared to their chance levels). These descriptive statistics also suggest that the majority of errors made during manipulation computations in the dynamic change detection task stem from non-target confusions.

2.3 Experiment 2 - Durability of Representations

The disparity in performance observed between set sizes 2 vs. 3 and 4 across the various swaps may result from differences in the strength of representations. Mainly, observers may be able to form durable representations of 2 items, which allows them to be manipulated without any cost. In contrast, representations of 3 and 4 items may not be durable to begin with, which makes them vulnerable to binding failures when operated upon. The experiments described in Section 2.3 address this concern.

In Experiment 2a, participants were allowed an unlimited amount of time to view the initial memory display, so that they would be able to form durable representations of all set sizes. In Experiment 2b, participants were able to control the onset of each swap, allowing them ample time to consolidate all representations after performing each manipulation computation. By allowing participants to set the pace of the encoding and consolidation periods, Experiments 2a-b sought to improve the strength of the (to-be) manipulated representations.

2.3.1 Experiment 2a – Unlimited Viewing

The differential effects observed when manipulating larger (i.e., 3 and 4) vs. smaller set sizes (i.e., 2) may not necessarily reflect differential costs in updating VWM representations. Rather, the systematic decrease in performance for set size 4 compared to set size 2 displays may stem from insufficient encoding of the memory display. Though memory displays of up to 12 items in static change detection tasks are typically presented for as short as 100 ms (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001), the 500 ms on-time used throughout our dynamic change detection tasks may not have allowed participants to form representations (particularly for the larger set sizes) that are strong enough to be subsequently manipulated. Therefore, in Experiment 2a, participants completed a dynamic change detection task in which they could control how long each memory display remained on the screen during the encoding period.

Methods:

Sixteen participants completed 150 trials of a dynamic change detection task identical (delayed-identification response) to that used in Experiment 1b, with the following exceptions (Figure 5). First, instead of having a fixed 500 ms presentation of the memory display, participants were able to control how long the stimuli were shown for by making a key press when they were ready to proceed. Second, once this key press was made, all stimuli were covered by identical colorful masks (1.5 x 1.5 ° of visual angle). This mask was used to disrupt representations stored in iconic memory and to prevent the after-effects that may have resulted from lengthy viewing times. These masks occluded the objects for the remaining duration of the trial (from the consolidation display until the target display) and moved with the objects as they swapped positions.

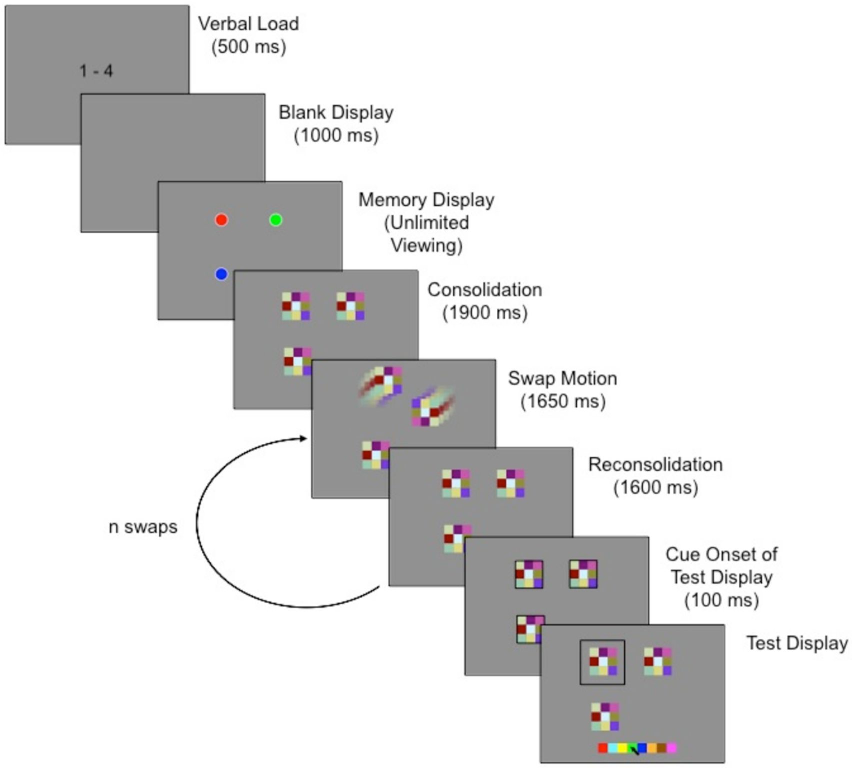


***Figure 5*. Schematic of dynamic change detection task (with delayed identification response) used in Experiment 2a. Participants were able to control the amount of time that the memory display was shown for. To prevent potential after effects from occurring, colorful masks were used instead of circular outlines.**

Results:

I first present data analysis describing how long participants chose to view the memory display, while encoding the to-be-remembered items (Figure 6). A 3 (set size) x 5 (number of swaps) within-subjects ANOVA conducted on response times revealed a significant main effect of set size, $F(2,30)=44.09$, $p<.001$, $\eta_p^2=.75$. Viewing duration for set size 2 displays were significantly shorter than set size 3 displays, $F(1,30)=39.67$, $p<.05$, and set size 4 displays, $F(1,30)=53.86$, $p<.05$. Viewing durations for set size 3 displays were also significantly shorter than set size 4 displays, $F(1,30)=25.96$, $p<.05$. The ANOVA failed to reveal any significant effects of number of swaps or interaction of set size by number of swaps. This was expected, as participants were never informed ahead of time as to the number of swaps that would take place in a given trial.

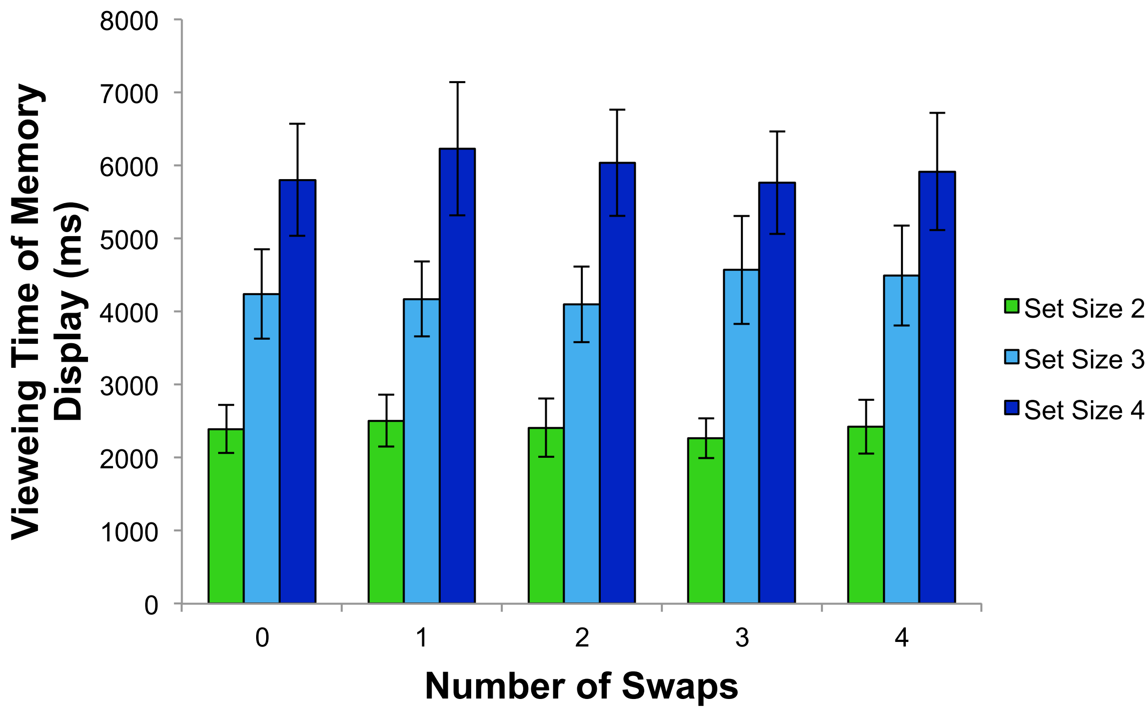


***Figure 6*. Amount of time elapsed for viewing initial memory display in Experiment 2a - dynamic change detection task (with delayed identification response method). Encoding time increased as a function of set size.**

To investigate costs associated with manipulating these representations, I performed a 3 (set size) x 5 (number of swaps) within-subjects ANOVA on performance accuracy (Figure 7). This analysis yielded a significant main effect of set size, $F(2{,}30)=17.48$, $p<.001$, $\eta_p^2=.54$. Accuracy was highest for set size 2 displays compared to set size 3 displays, $F(1{,}30)=10.13$, $p<.05$, and set size 4 displays, $F(1{,}30)=29.34$, $p<.05$. Furthermore, accuracy for set size 3 displays was also higher compared to set size 4 displays, $F(1{,}30)=9.43$, $p<.05$. The ANOVA also produced a significant main effect of number of swaps, $F(4{,}60)=12.48$, $p<.001$, $\eta_p^2=.45$. Performance was higher on the static condition compared to the dynamic conditions, $F(1{,}52)=15.19$, $p<.05$. Lastly, the ANOVA revealed a significant interaction of set size by number of swaps, $F(8{,}120)=4.56$, $p=0.003$, $\eta_p^2=.23$. A significant linear (set size 2) x linear (set sizes 3 and 4) contrast was observed, $F(1{,}120)=24.20$, $p<.05$, suggesting differential effects for manipulating 2 items, compared to manipulating 3 or 4.

The results of Experiment 2a converge with those observed throughout Experiments 1a-b. And, the manipulation costs observed here are not attributable to limited viewing time of the memory display.

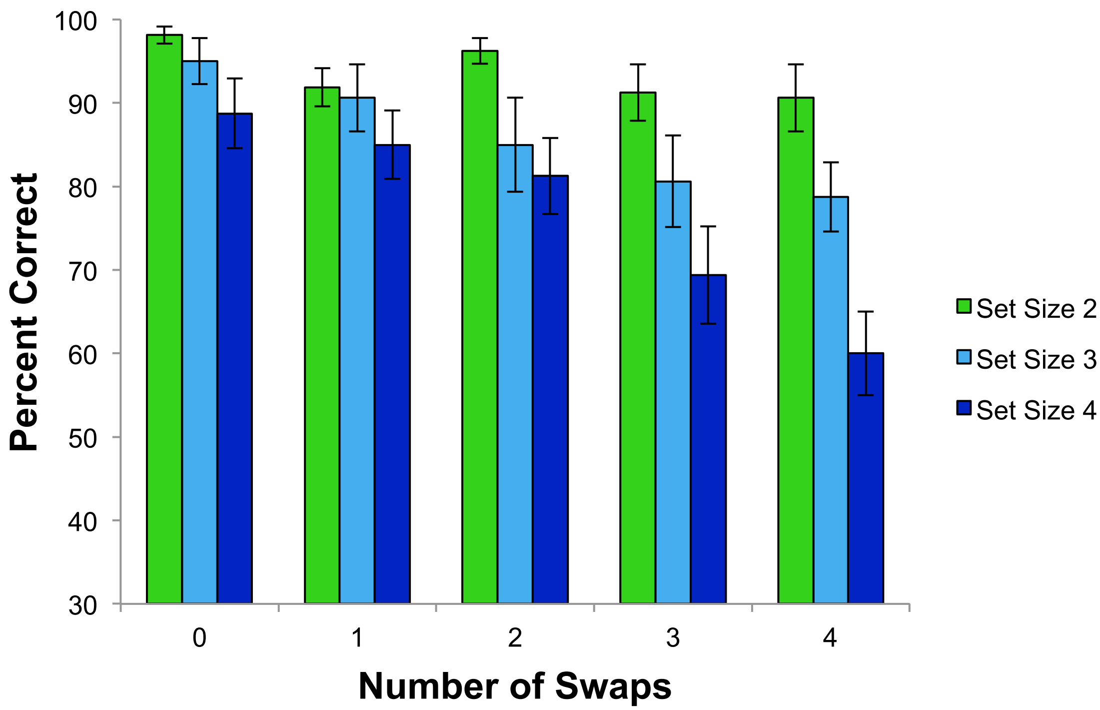


Figure 7**. Results (percent correct) observed in Experiment 2a – Unlimited viewing (with delayed identification response method). Once more, a disparity was observed in performance accuracy when manipulating 2 vs. 3 or 4 items.**

2.3.2 Experiment 2b – Self-Paced Onset of Movement

The results of Experiment 2a suggest that there is little to no cost for manipulating 2 vs. 3 or 4 items when given sufficient time to form durable representations during encoding. However, this pattern of performance may result from the limited consolidation time allowed between swaps. Specifically, the 1650 ms dwell period enforced between each swap may not have allowed participants to durably update their visual expectations for set sizes 3 and 4. In Experiment 2b, I allowed observers to control the initiation of each event in the trial, which enabled me to measure whether dwell time changed as a function of set size and number of swaps (e.g., swap 1, *dwell*, swap 2, *dwell*, test display).

Methods:

Fourteen participants completed 300 trials of a dynamic change detection task (probe response) identical to that used in Experiment 1a, with the following exceptions. First, participants rehearsed the verbal load out loud (as opposed to sub-vocally) throughout the duration of the trial, while being monitored by an experimenter. As such, participants were no longer required to report the identity at the end of each trial. Second, and most importantly, the dynamic change detection task used in Experiment 2b was self-paced, such that participants were able to control the onset of each swap by making a key press. The first swap, however, was always automated, to ensure that the consolidation period between the memory display and the first swap was constant across all trials.

Results:

The results of the self-paced experiment replicated those demonstrated in previous experiments (Figure 8). A main effect of set size was observed, $F(2,26)=42.73$, $p<.001$, $\eta_p^2=.77$, as participants were more accurate in set size 2 conditions, compared to set size 3, $F(1,28)=102.77$, $p<.05$, and set size 4, $F(1,26)=55.30$, $p<.05$, conditions. Performance was also higher on set 3 conditions relative to those for set size 4, $F(1,26)=13.37$, $p<.05$.

Furthermore, there was a significant main effect of number of swaps, $F(4,52)=24.90$, $p<.001$, $\eta_p^2=.66$, as performance was higher on the static condition compared to the dynamic conditions, $F(1,52)=24.26$, $p<.05$. Lastly, a significant interaction of set size x number of swaps, $F(8,104)=3.93$, $p=0.007$, $\eta_p^2=.23$, was observed once more, as demonstrate by a post-hoc contrast revealing differential effects for manipulating 2 items in VWM relative to manipulating 3 or 4, $F(1,104)=63.52$, $p<.05$.

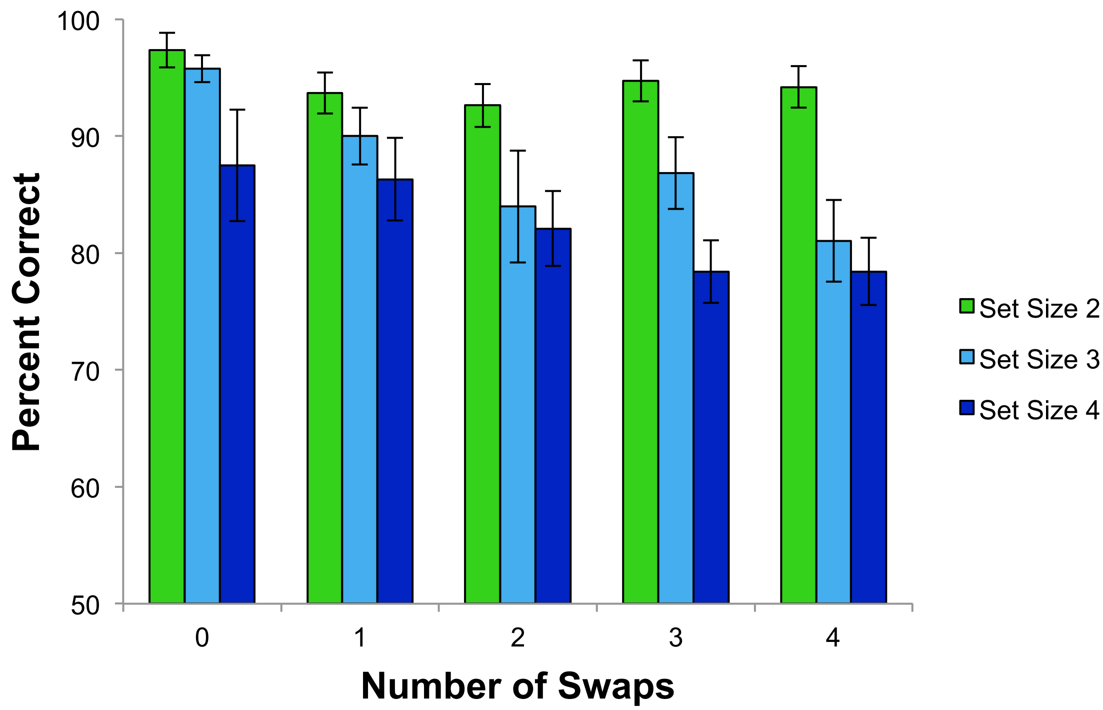


***Figure 8*. Results (percent correct) observed in Experiment 2b – Self-paced onset of movement (with probe response method).**

Furthermore, this pattern of results (higher accuracy for set size 2 vs. set sizes 3 and 4) is not attributable to a speed-accuracy tradeoff. A 3 (set size) x 4 (number of swaps) within-subjects ANOVA of the response times for initiating the swaps failed to reveal a significant main effect of set size, $F(2,26)=2.33$, $p=.13$, $\eta_p^2=.15$, a significant main effect of number of swaps, $F(3,39)=1.97$, $p=.16$, $\eta_p^2=.13$, or an interaction of set size by number of swaps, $F(6,78)=1.28$, $p=.29$, $\eta_p^2=.09$. Participants took just as long to initiate each swap across all conditions. Furthermore, these null results suggest that the two-digit load was effective in preventing the use of verbal strategies. If participants were indeed using verbal strategies to refresh and manipulate stimuli, RT's would be expected to increase as a function of set size. Lastly, the longest average RT was observed in the set size 4 – 1 swap condition and measured approximately 1600 ms. This value is within the 1650 ms dwell period used in the previous experiment, suggesting that participants had ample time to perform the manipulations in previous experiments.

2.4 Experiment 3 - Temporal Delay

The dynamic change detection task used here combines attributes of the traditional static change detection task with dynamic changes across time and space to simultaneously measure VWM storage and manipulation abilities. However, given that performance in this task is measured across a series of swaps, it is unclear whether decrements in memory accuracy are a function of the number of manipulations performed or with the passing of time associated with performing these manipulations.

In Section 2.4, I address this concern in two ways. First, I remove the active manipulation component from the dynamic change detection task, to investigate whether the same 2 vs. 3 and 4 item disparity would be observed when task demands are strictly placed on VWM storage ability (Experiment 3a). The results of this modification clarify whether the pattern of results observed throughout the previous experiments can be attributed to the active manipulation of information or to temporal decay. Second, I reintroduce the active manipulation demands to the dynamic change detection task, but enforce variable dwell periods to ensure that all trials are equidurant (Experiment 3b). In so doing, I address whether the 2 vs. 3 and 4 item manipulation disparity results from an interaction of set size and temporal decay.

2.4.1 Experiment 3a – No Active Manipulation

Performance decrements in my dynamic change detection task may not necessarily reflect costs associated with manipulating information in VWM. Rather, accuracy may gradually decrease across swap conditions due to the passage of time. This remains a moot point in the VWM literature, as prior research provides evidence both supporting (Cornelissen & Greenlee, 2000; Lee & Harris, 1996; Paivio & Bleasdale, 1974) and opposing (Zhang & Luck, 2009) a gradual decay hypothesis.

To ensure that performance decrements across the number of swaps in the dynamic change detection task do not result from the temporal decay, demands to actively manipulate information were eliminated in Experiment 3a (objects did not swap positions). By removing the active manipulation component, performance in Experiment 3a strictly represents storage ability across varying delay periods.

Methods:

Fourteen participants completed 300 trials of a variant of the task (delayed identification response) identical to that used in Experiment 1b, with one main exception. Unlike previous experiments (Figure 9a), pairs of objects did not swap positions at any point during the trial (Figure 9b). Instead, once the memory and consolidation displays were presented, the circular outlines remained stationary on the screen for a variable period of time before the onset of the test display. The duration of these dwell times were equivalent to the amount of time elapsed when performing 0-4 swaps in previous experiments.

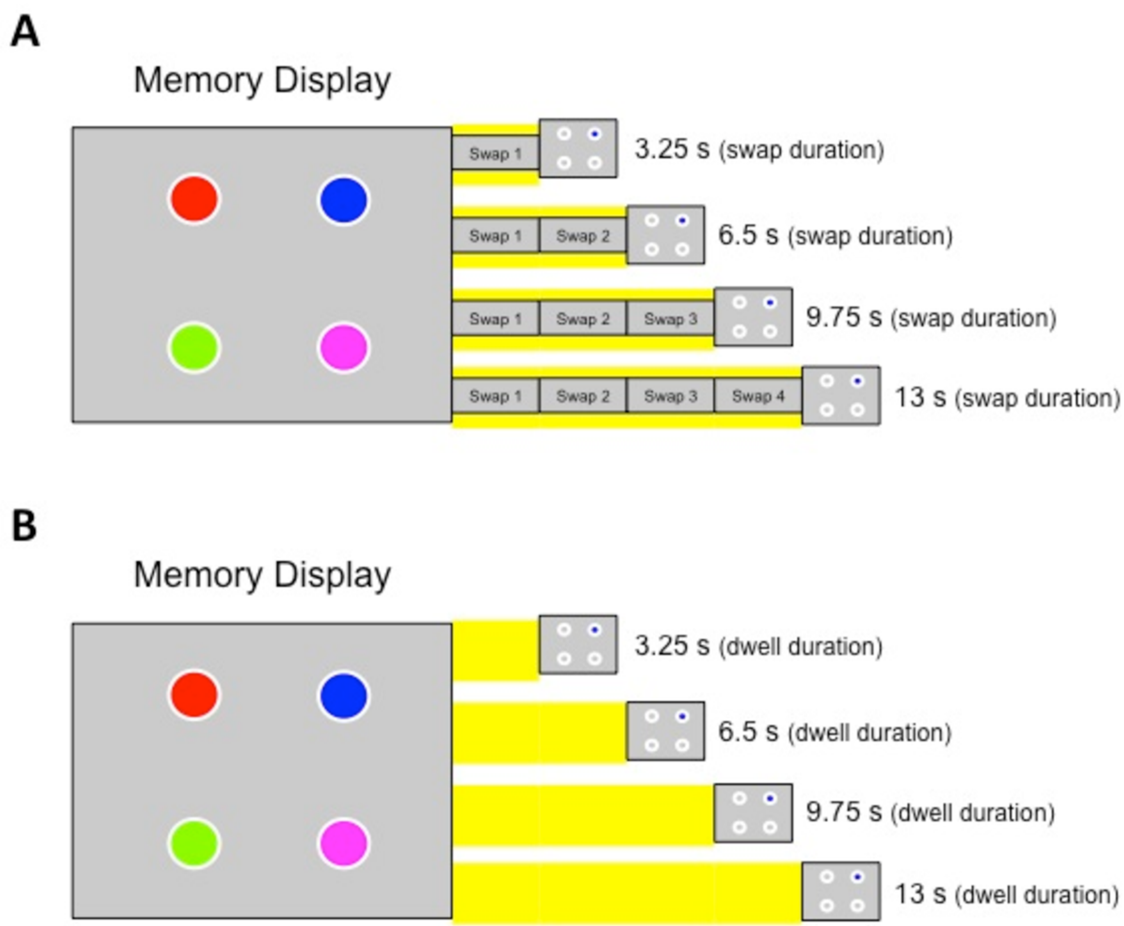


***Figure 9*. A) Timeline of events in typical dynamic change detection task. After the offset of the memory display, pairs of objects swap positions up to 4 times before the onset of the test display, leading to varying trial durations. B) Timeline of events in Experiment 3a. After the offset of the memory display, objects did not swap positions. Instead, they remained stationary on the screen for varying dwell durations until the test display appeared. The dwell durations were based on the amount of time elapsed for 0-4 swaps to take place in typical dynamic change detection task trials.**

Results:

A 3 (set size) x 5 (dwell time) within-subjects ANOVA conducted on performance accuracy (Figure 10) revealed a significant main effect of set size, $F(2,26)=17.02$, $p=.001$, $\eta_p^2=.57$. Post-hoc contrasts revealed that performance was higher for set size 2 compared to set size 3, $F(1,26)=9.11$, $p<.05$, and set size 4, $F(1,26)=16.86$, $p<.05$. Furthermore, performance accuracy was higher for set size 3 compared to set size 4, $F(1,26)=21.14$, $p<.05$. The ANOVA failed to reveal a significant main effect of number of swaps, $F(4,52)=2.74$, $p=.06$, $\eta_p^2=.17$, or a significant interaction of set size by number of swaps, $F(8,104)=1.19$, $p=.33$, $\eta_p^2=.08$. Though the observed effect of number of swaps can be considered marginally significant ($p=.06$), it is unlikely that temporal decay underlies the manipulation based costs observed in the previous experiments (given the significance level of the interaction effect observed here, $p=.33$). The results of this experiment suggest that the 2 vs. 3-4 item disparity observed in previous experiments requires the active manipulation of information.

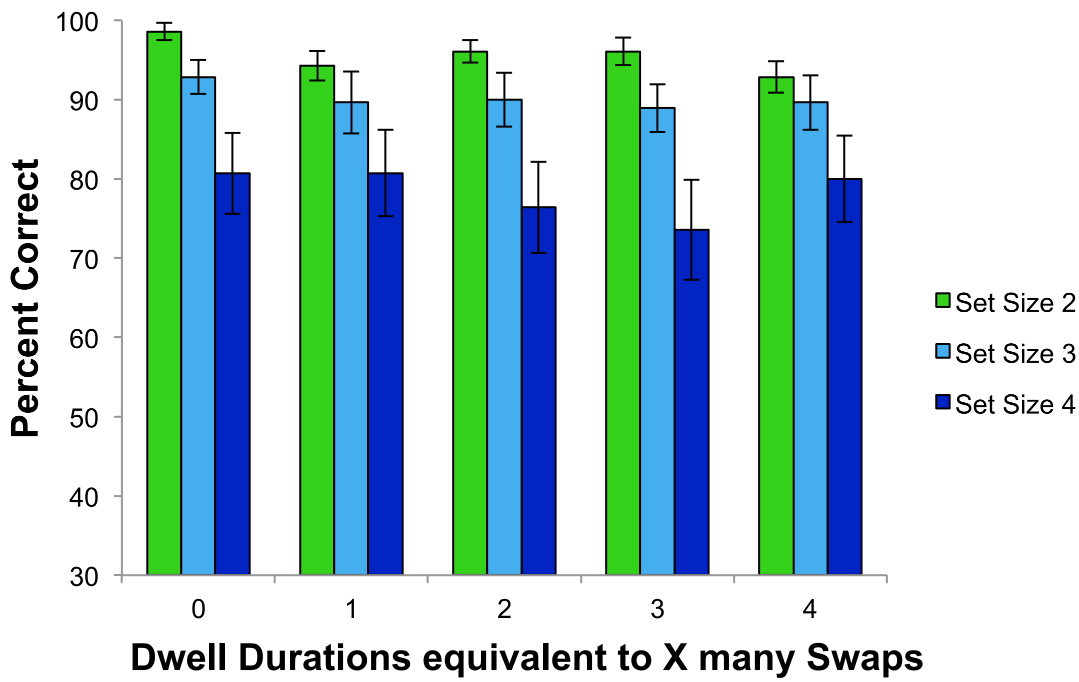


Figure 10. **Results (percent correct) observed in Experiment 3a – No active manipulation (with delayed identification response). Removing the active manipulation component in the task eliminates the 2 vs. 3 and 4 item disparity observed in previous experiments.**

2.4.2 Experiment 3b – Equidurant Trials

The results of Experiment 3a suggest that the 2 vs. 3-4 item disparity observed throughout this chapter cannot simply be attributed to temporal delay. Rather, the pattern of costs observed in the dynamic change detection task requires the active manipulation of information. However, this does not rule out the possibility that temporal delay may have an effect when manipulation demands are present. For example, these factors can interact in such a way where manipulating 2 items over a period of time does not lead to any costs. However, when manipulating 3 or 4 items over this same period, temporal delay interacts with manipulation ability and results in a systematic decrease in performance accuracy. In Experiment 3b, I address this concern by having participants complete a typical dynamic change detection task in which trial durations are held constant across all conditions.

Methods:

Nineteen participants completed 150 trials of a dynamic change detection task (probe response) identical to that used in Experiment 1a, with the following exceptions. First, participants were instructed to rehearse the verbal load out loud throughout the course of the entire trial. Second, a dwell period was enforced between the last swap and the onset of the target display, to control for total trial duration (Figure 11). During this dwell period, the circular white outlines remained stationary on the screen. All trials lasted approximately 16.9 seconds.

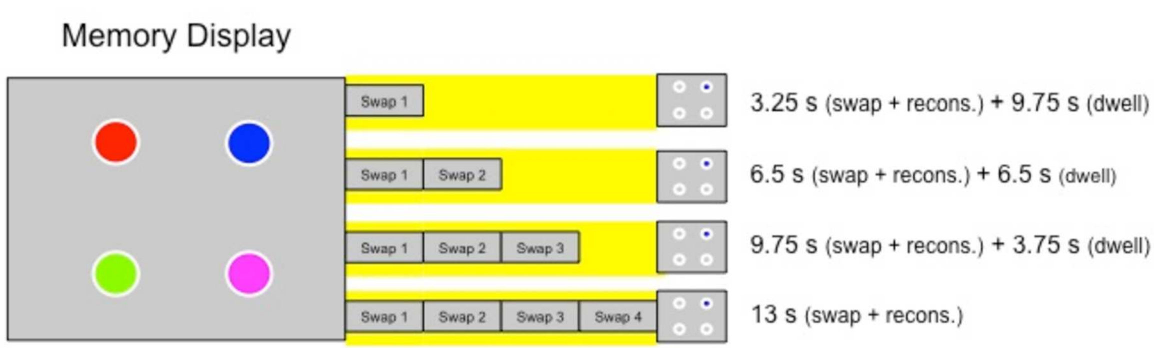


***Figure 11*. Timeline of events in Experiment 3b – Equidurant trials (with probe response method). After the offset of the memory display, pairs of objects swapped positions up to 4 times. Varying dwell periods were enforced after all swaps were completed. During these periods, the circular outlines remained stationary.**

Results:

The results of Experiment 3b (Figure 12) replicate those observed in the previous dynamic change detection experiments. The 3 (set size) x 5 (number of swaps) within-subjects ANOVA yielded a significant main effect of set size, $F(2,36)=28.08$, $p<.001$, $\eta_p^2=.61$. Performance decreased as a function of set size, as accuracy for set size 2 conditions were superior to set sizes 3, $F(1,36)=18.98$, $p<.05$, and 4, $F(1,36)=43.16$, $p<.05$, and set size 3 performance was superior to set size 4, $F(1,36)=13.88$, $p<.05$. Once more, a significant main effect was observed for the number of swaps, $F(4,72)=11.38$, $p<.001$, $\eta_p^2=.39$, as accuracy was higher when no swaps occurred compared to when one did take place, $F(1,72)=47.20$, $p<.05$. The ANOVA also revealed a significant set size x number of swaps interaction, $F(8,144)=2.25$, $p<.03$, $\eta_p^2=.11$, providing support for the independence in costs for storing and manipulating items in visual WM. Once more, differential effects were observed for manipulating 2 items vs. 3 and 4, as little to no cost was observed for the smallest set size, though performance worsened across conditions for the larger set sizes, $F(1,144)=16.18$, $p<.05$.

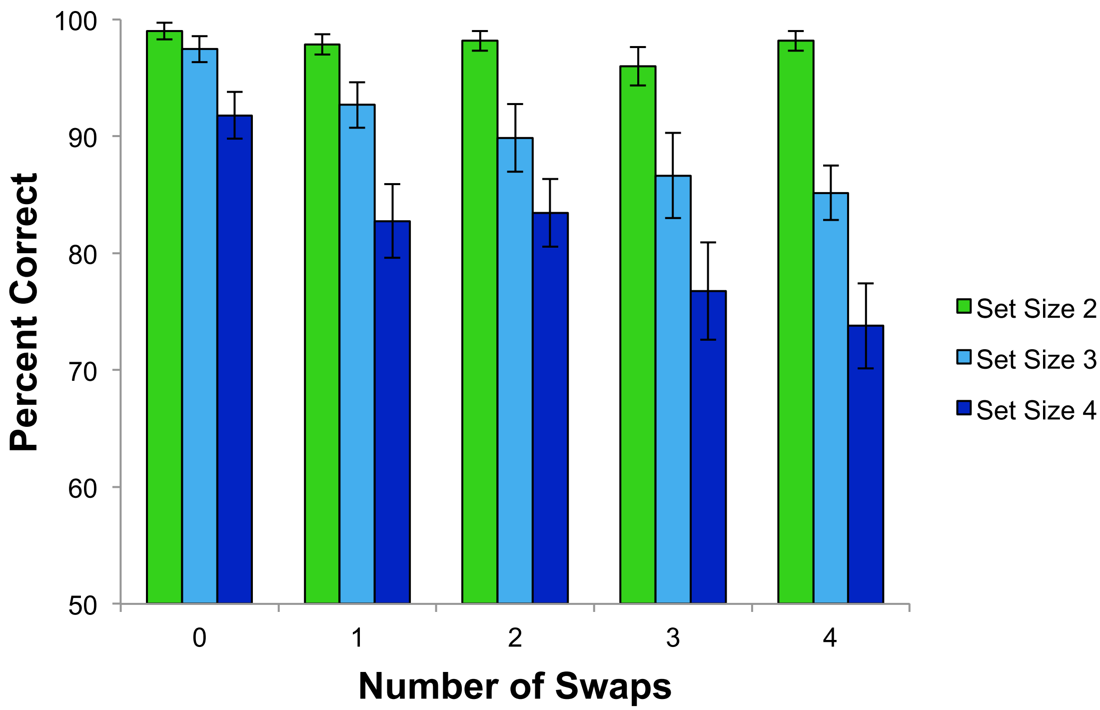


***Figure 12*. Results (percent correct) observed in Experiment 3b – Equidurant trials (with probe response method).**

2.5 Experiment 4 - Interference

Across all experiments described in this chapter, participants were presented with varying set sizes of colored circles that swapped positions. This design may prove problematic as it may introduce sources of interference that separately hinder the processing of featural or spatial information. Specifically, it would be unclear whether performance decrements in the dynamic change detection task truly reflect costs of *updating* the spatial-featural binding of objects or if such costs simply arise due to insufficient processing of these individual components.

In Section 2.4, I control for two possible sources of interference. First, in Experiment 4a, I decrease the perceptual similarity among items in the featural dimension by presenting memory displays consisting of categorically different shapes (instead of colored circles). In so doing, I decrease the level of confusability among items within the display. Additionally, this modification provides a way to investigate whether the pattern of results observed in the previous experiments truly represent manipulation costs and can generalize to another feature dimension or whether those costs are specific to color-space bindings. Second, in Experiment 4b, I decrease the extent to which proactive interference may hinder spatial processing by freeing object motions while disallowing objects from swapping positions. That is, I unrestrict motion dynamics by allowing objects to move to unoccupied locations.

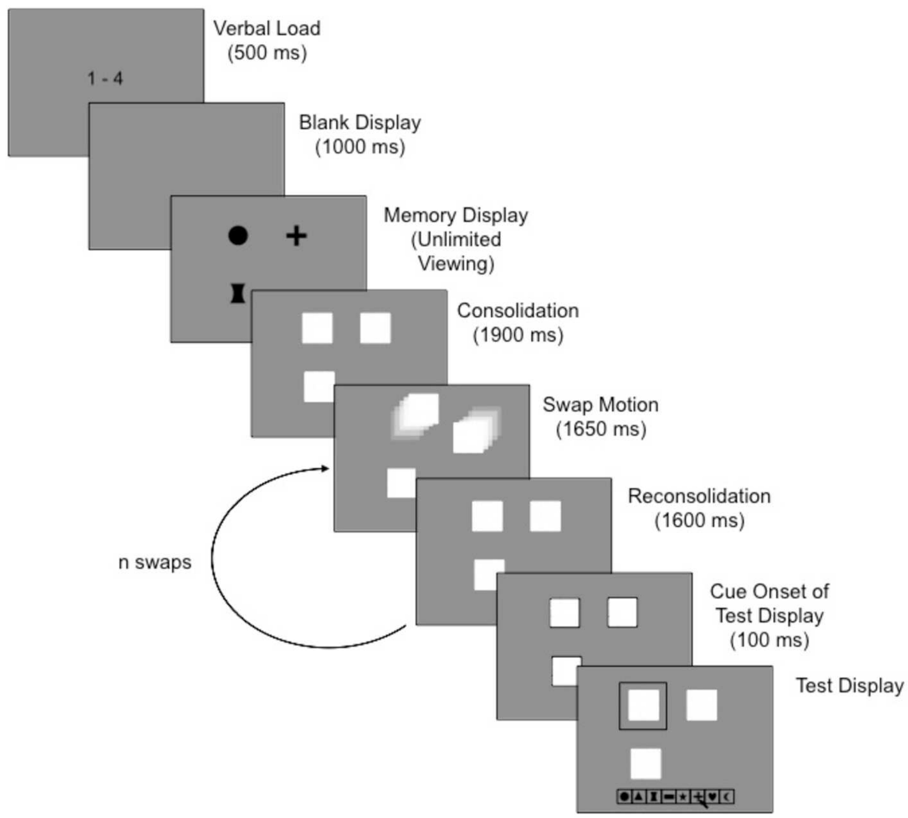
2.5.1 Experiment 4a – Shapes

To address possible interference in the processing of featural information, I reduced confusability among memory items by using perceptually dissimilar stimuli. As opposed to memory displays consisting of colored circles, participants were presented with categorically different shapes.

Methods:

Eighteen participants completed 300 trials of a dynamic change detection task (delayed identification response) similar to that used in Experiment 1b, with the following exceptions (Figure 13a). First, participants were presented with categorically different shapes (Figure 13b: circle, triangle, hourglass, rectangle, star, cross, heart, moon). These shapes were all colored black and subtended an average of 1.72° by 1.72° of visual angle. Second, once the memory display was presented, a white square (1.72° x 1.72° of visual angle) appeared at the location of each item, giving the impression that the memory items were being occluded. During each swap, pairs of occluders underwent smooth motion to trade positions. A black rectangular outline (2.45 by 2.45 °) surrounding a given occluder was used in the test display to indicate the target item. Participants were instructed to report the identity of the target by using the mouse cursor to click on an option bar that horizontally presented all possible shapes that could have appeared in the memory display.

a


1 - 4
Verbal Load
(500 ms)
Blank Display
(1000 ms)
Memory Display
(Unlimited
Viewing)
Consolidation
(1900 ms)
Swap Motion
(1650 ms)
Reconsolidation
(1600 ms)
n swaps
Cue Onset of
Test Display
(100 ms)
Test Display

b

***Figure 13*. a) Schematic of dynamic change detection task (with delayed identification response) used in Experiment 4a. Memory displays in this task consisted of categorically different shapes. b) Stimulus set used in Experiment 4a.**

Results:

The results of a 3 (set size) x 5 (number of swaps) within-subjects ANOVA (illustrated in Figure 14) produced a similar pattern of results, compared to previous experiments that displayed colored circles. This analysis yielded a main affect of set size, $F(2,34)=151.79$, $p<.001$, $\eta_p^2=.90$. Post-hoc contrasts revealed that accuracy was highest for set size 2 conditions (set size 2 vs. set size 3: $F(1,34)=78.82$, $p<.05$; set size 2 vs. set size 4: $F(1,34)=187.22$, $p<.05$) and lowest for set size 4 conditions (set size 3 vs. set size 4: $F(1,34)=160.64$, $p<.05$). The ANOVA also yielded a main effect of number of swaps, $F(4,68)=36.17$, $p<.001$, $\eta_p^2=.68$. Performance accuracy was highest for the static condition vs. the dynamic conditions, $F(1,68)=77.32$, $p<.05$. Lastly, the ANOVA yielded a significant interaction of set size x number of swaps, $F(8,136)=4.00$ $p=.003$, $\eta_p^2=.19$. A post-hoc linear x linear trend analysis revealed a significant effect, $F(1,136)=31.86$, $p<.05$, where little-to-no cost was observed for manipulating 2 items, compared to the systematic decrease in performance observed for manipulating 3 or 4 items.

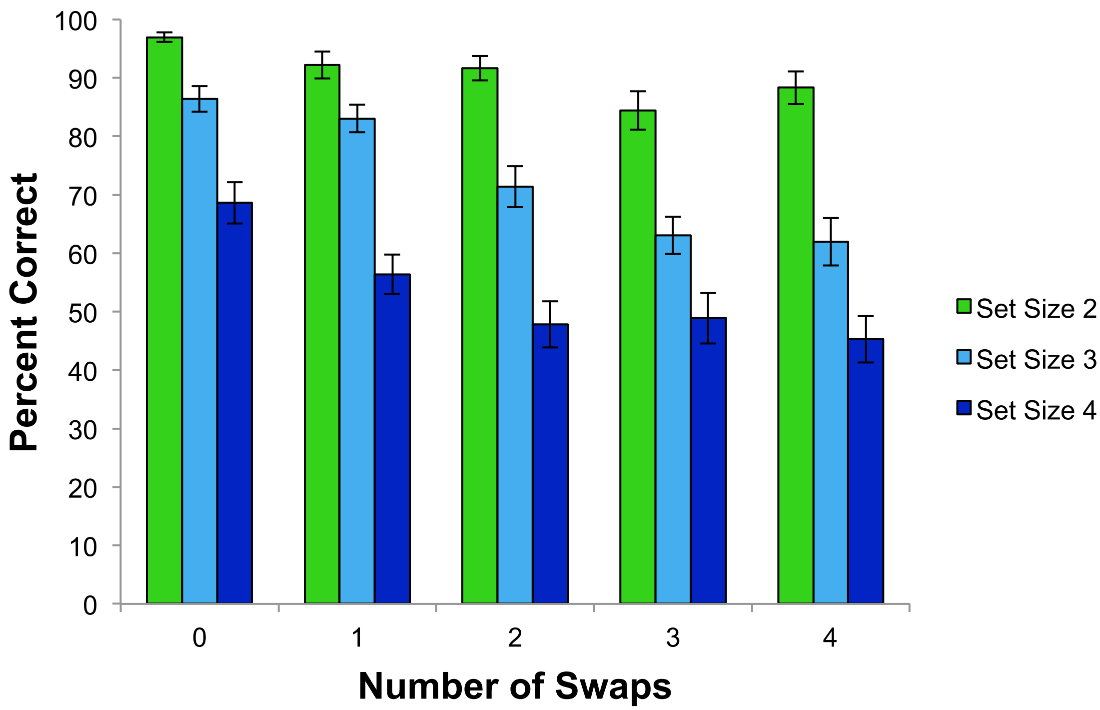


***Figure 14*. Results (percent correct) observed in Experiment 4a – Shapes (with delayed identification response method). The pattern of results are similar to those observed for manipulating colored circles.**

2.5.2 Experiment 4b – Non-Swappers

In the dynamic change detection task, participants are instructed to update featural-spatial bindings of objects as they swap positions. However, such swapping may introduce proactive interference, such that an object that previously occupied a given location may hinder the subsequent processing of another object (its swap partner).

To address this concern, objects in Experiment 4b were presented among a 4 x 4 matrix of circular outlines that represented 16 possible locations that could be occupied by memory items. When undergoing smooth motion, pairs of objects were not allowed to swap positions. Instead, each object moved towards a previously unoccupied location in the grid. As such, this "non-swappers" design provided a way to reduce the amount of proactive interference that may otherwise occur from objects coming to occupy the same locations. This modification also reduced reliance on global properties of the display, as the configuration of memory items changed unpredictably with each swap.

Methods:

Seventeen participants completed 450 trials of a dynamic change detection task requiring a delayed identification response. As per previous experiments, each trial began with the onset of a white fixation cross (0.5° x 0.5°) that was presented for 500 ms. After an interstimulus interval of 100 ms, participants were presented with a two digit verbal load that they were instructed to vocally rehearse throughout the duration of each trial. These digits remained on the screen for 500 ms and were followed by the memory display.

Displays in Experiment 4b (Figure 15) differed from those used in previous experiments, mainly because the to-be-remembered items were presented among a 4 x 4 grid of circular placeholders (situated at the center of the screen). These placeholders (center to center distance between circular outlines: 2.94 ° of visual angle) were the same size and color as the memory items (size: 0.98 ° of visual angle; thickness of white circular outline: 0.25 ° of visual angle), and represented the possible locations that could be occupied. Moreover, this grid remained on the screen throughout the entire duration of each trial.

During the encoding period, set sizes of 2-4 items occupied locations marked by placeholders in the grid. Each item was presented in a random location within a given quadrant of the 4 x 4 grid (only one object could occupy a given quadrant at a time). This memory display was presented for 500 ms, after which the colors disappeared, leaving behind the grid of placeholders. This consolidation display remained on the screen for 1900 ms, after which pairs of objects proceeded to move 0 to 4 times to a previously unoccupied placeholder location (rate of 100 pixels per frame). These objects followed a linear trajectory and moved towards an unoccupied placeholder that was located in the same quadrant as its corresponding swap partner (e.g. if object A appeared in upper left quadrant, object B could move towards any placeholder in the upper left quadrant other than the one previously occupied by object A). During a given swap, the inside of moving objects were filled in with the same gray color as the background, giving the impression that these objects were moving in front of the grid of circular placeholders. Once all swaps were complete, participants were presented with the test display.

Similar to previous experiments, a blank square outline (2.45 by 2.45 ° of visual angle) was used to cue the target item. However, on one third of all trials, the cue was presented at an unoccupied placeholder that was adjacent to the target location (in the same quadrant). On these trials, the correct answer was a blank circle. These trials were included to ensure that updating both the featural and the spatial information of the objects was required in the task, as opposed to generally keeping track of which quadrant each object moved towards.

Once more, participants reported the identity of the cued item by clicking on an option bar. This option bar presented all possible colors that could have appeared in the memory display, as well as a white circular outline. Participants were instructed to click on this outline option when they believed the cue appeared at an unoccupied placeholder location.

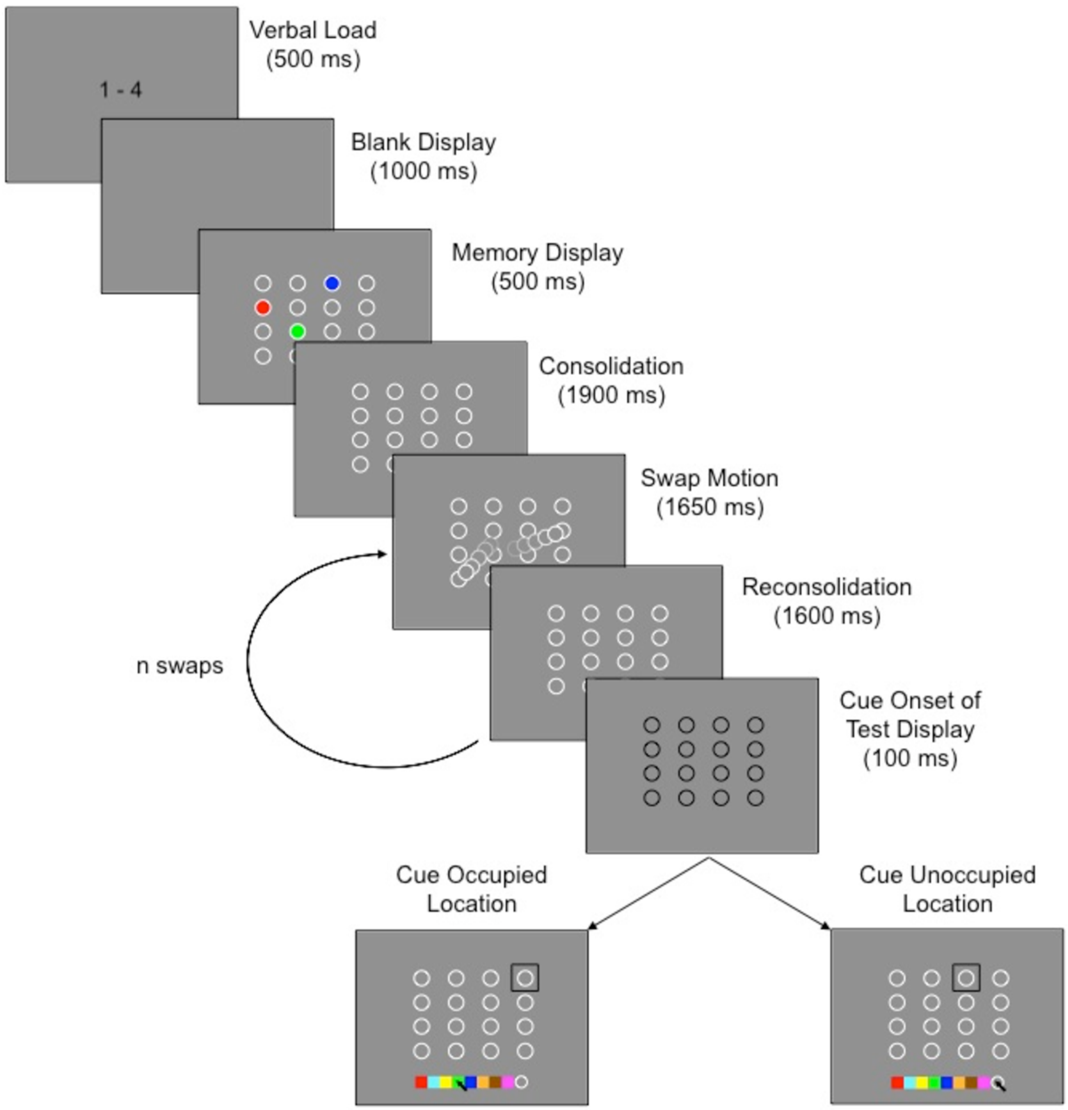


Figure 15. **Schematic of dynamic change detection task (with delayed identification response) used in Experiment 4b – Non-swappers. All displays throughout the trial consisted of a 4 x 4 grid of white circular placeholders, which demarcated all possible object locations. Objects in this task did not**

swap positions. Instead, they followed a linear trajectory towards an unoccupied location. During the test phase, a cue appeared at either an occupied or unoccupied location. Where appropriate, participants had to report the color of the cued item or identify it as an unoccupied location

Results:

Target Cued Conditions (correct responses):

I first present the data for conditions where the cue appeared at the (occupied) target location. A 3 (set-size) x 5 (number of swaps) ANOVA conducted on performance accuracy (Figure 16) yielded a main effect of set size, $F(2,32)=102.26$, $p<.001$, $\eta_p^2=.87$. Post-hoc contrasts revealed that accuracy was highest for set size 2 conditions (set size 2 vs. set size 3: $F(1,32)=51.72$, $p<.05$; set size 2 vs. set size 4: $F(1,32)=135.47$, $p<.05$) and lowest for set size 4 conditions (set size 3 vs. set size 4: $F(1,32)=101.26$, $p<.05$). The ANOVA also revealed a main effect of number of non-swaps, $F(4,64)=33.65$, $p<.001$, $\eta_p^2=.68$. Post-hoc contrasts revealed that accuracy was highest for the static condition compared to the dynamic conditions, $F(1,64)=47.14$, $p<.05$. Furthermore, a significant interaction of set size by number of swaps was observed, $F(8,128)=4.00$, $p=.003$, $\eta_p^2=.20$. Once more, post-hoc linear trend analyses demonstrate little-to-no cost for manipulating 2 items compared to a systematic decrease in accuracy for manipulating 3 and 4 items, $F(1,128)=40.22$, $p<.05$.

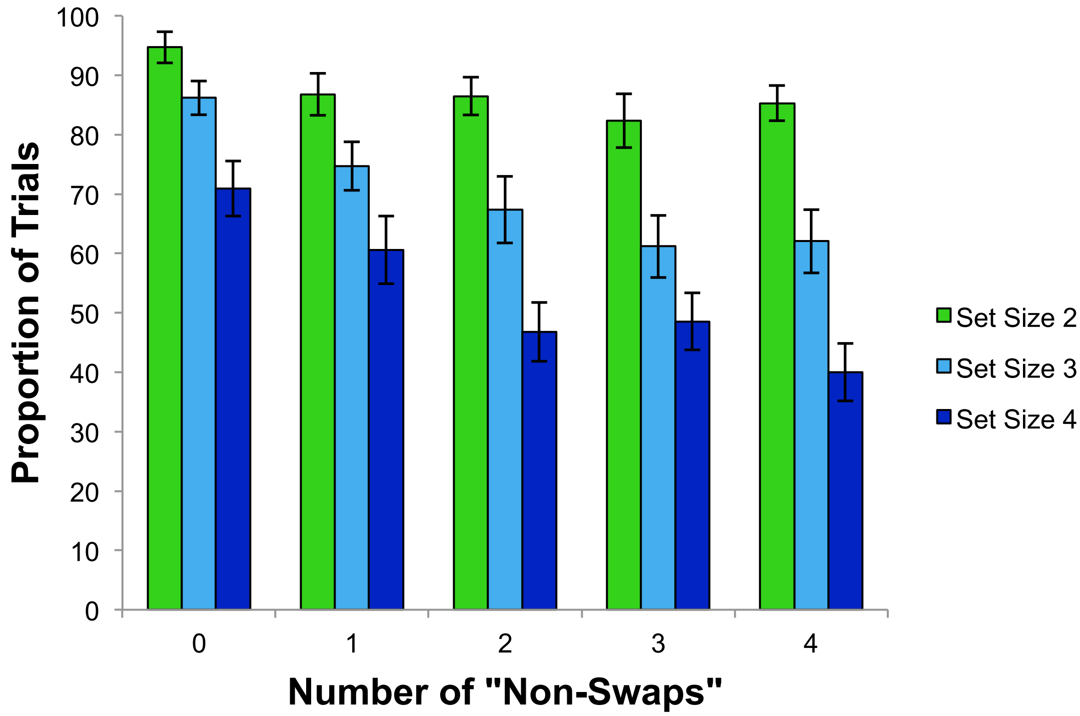


***Figure 16*. Results (percent correct) observed in occupied cued location conditions in Experiment 4b – Non-swappers (with delayed identification response method).**

Target Cued Conditions (incorrect responses):

Similar to previous experiments, incorrect responses for target cued conditions may stem from non-target confusion errors and random guess errors. However, given that the option bar in Experiment 4b included an additional response choice of "unoccupied location", incorrect responses may have additionally resulted from errors where participants mistakenly identified an occupied target location as unoccupied (spatial localization error). The majority of incorrect responses made in Experiment 4a stemmed from non-target confusion errors (approximately 56% of all incorrect responses). Random guess errors constituted the second most frequent error type underlying incorrect responses (approximately 29% of all incorrect responses). Spatial localization errors constituted the least frequent type of mistake leading to an incorrect response (approximately 15% of all incorrect responses). These results replicate the results of Experiment 1b and suggest that non-target confusions are the most frequent source of incorrect responses.

Unoccupied Location Cued Conditions (correct responses)

Next, I analyze the data for conditions where the cue appeared at an unoccupied location. Any response where a participant chose a color from the option bar constituted an incorrect response. On average, accuracy rates for these conditions were very high (approximately 95% correct across all conditions).

A 3 (set-size) x 5 (number of swaps) ANOVA conducted on performance accuracy (Figure 17) yielded a main effect of set size, $F(2,32)=7.31$, $p=.007$, $\eta_p^2=.31$. Post-hoc contrasts failed to reveal a significant difference in accuracy rates between set sizes 2 and 3, $F(1,32)=0.77$, $p>.05$, though performance was higher for these set sizes conditions compared to set size 4 conditions, $F(1,32)=9.37$, $p<.05$. In contrast, the ANOVA failed to demonstrate a significant main effect of non-swaps, $F(4,64)=2.81$, $p=.06$, $\eta_p^2=.15$, or a significant interaction of set size by number of non-swaps, $F(8,128)=1.00$, $p=.42$, $\eta_p^2=.06$. These results indicate that observers maintained very accurate representations for the location of each item.

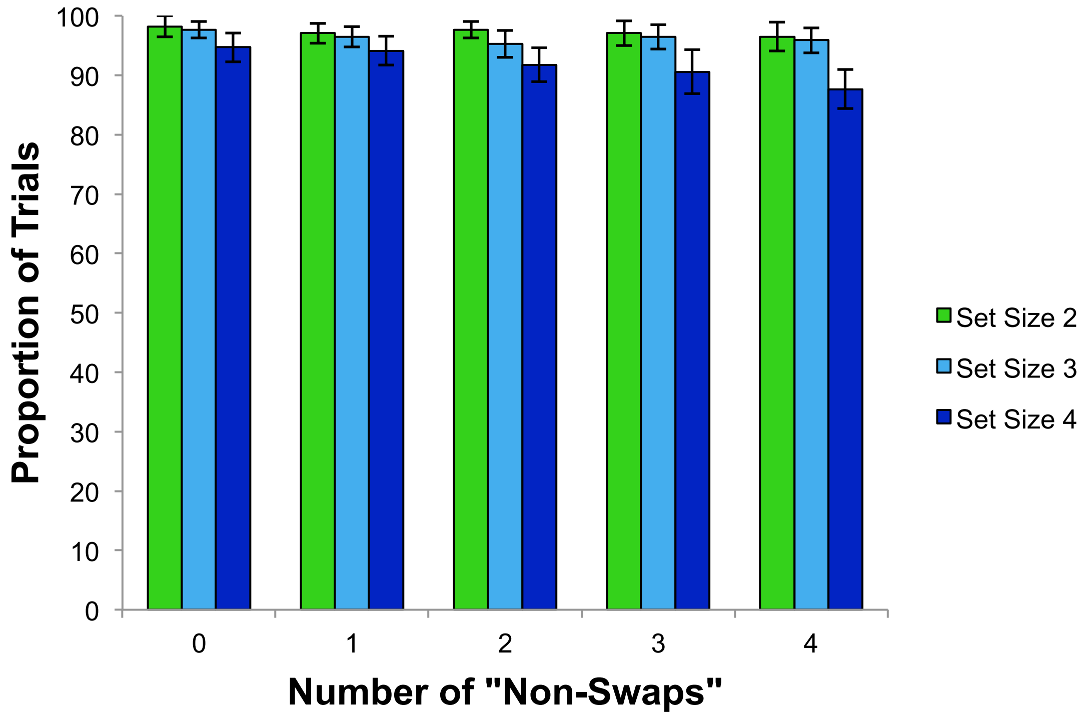


***Figure 17*. Results (percent correct) observed in unoccupied cued location conditions in Experiment 4b – Non-swappers (with delayed identification response method).**

2.6 Discussion

Though exploring costs in working memory (both verbal and visual) has been effective for characterizing the structure of the system, work within the visual domain has placed emphasis on determining limits imposed on storage abilities, as opposed to manipulation. Here, I developed a novel paradigm for investigating costs associated with manipulating information. Specifically, I investigated whether the ability to update an object's color information to a novel location produces a memory decrement compared to when no manipulation is required.

Across eight experiments, I observed costs associated with manipulating information in VWM. Specifically, dynamically updating the position and color information for moving targets resulted in an additive cost with each movement for set sizes of both 3 and 4 targets. This cost was differentially influenced by the set size of stored items and the number of manipulations performed, as little-to-no cost was observed for manipulating 2 items. This pattern of results persists when controlling for factors known to constrain abilities in working memory (both verbal and visual domains), including durability of representations, temporal delay, and interference.

A 2-item Manipulation Limit?

The results of Experiments 1-4 consistently demonstrated differential costs as a function of set size and number of manipulations when observers performed updates for multiple items in VWM. However, further investigation is required prior to claiming a 2-item limit in VWM manipulation ability. Though Experiment 4a (Shapes) demonstrates that the observed pattern of manipulation costs can be generalized to cases other than color-location bindings, it is unclear whether the same pattern would be observed for instances of feature-feature (e.g. color-shape) bindings.

Furthermore, intuition may argue against a 2-item manipulation limit, given that performing manipulations in our every day lives does not seem difficult or effortful. However, in the real world, additional sources of information may be available to us that can help overcome manipulation constraints. These sources may include information about objects stored in long-term memory (e.g. I know that nargles are always blue, therefore this nargle cannot be black) or configural information (e.g. if an object moves to a novel location, but its position relative to other objects in the display remains the same, one can simply use the original configural information to infer the relative location of the manipulated object). When additional sources of information are not available, we may experience difficulty in performing these manipulations. For example, comparing cis- and trans- isomers in chemistry requires individuals to mentally update the spatial-featural bindings of molecules. This process is notoriously difficult (Stieff & Raje, 2010), potentially due to a lack of a priori or configural information that is available to aid these manipulations.

Additionally, the preservation of 2 items may be attributed to various strategies emerging from the specific swap motions used in the dynamic change detection task. Specifically, swapping may allow participants to chunk items into a single unit. In this case, what might actually be a 1-chunk manipulation limit appears to be a 2-item limit. This is unlikely, however, given that manipulating 2 items in Experiment 4b (non-swappers) produced the same pattern of results even when items moved to novel, unoccupied locations. Lastly, this 2-item manipulating privilege is observed in experiments using other paradigms where swap motion is unconstrained. For example, Horowitz and colleagues (2007) conducted a multiple object tracking (MOT) experiment, in which targets were unique animals. Identity information was occluded and stimuli randomly moved across the screen. Participants had to identify the location of a particular target, based on its identity (i.e. "where is the zebra?"). As such, the described experiment presents itself on the continuum of the dynamic change detection task, on the end where movement dynamics are unconstrained. Similar to the results observed here, Horowitz et al. (2007) found that performance was limited to an average of approximately two objects.

Neural Underpinnings of Manipulation Costs:

Neural synchrony has been conceptualized as the underlying mechanism that allows for the binding of various object features into a single representation, both in perception (Hummel & Biederman, 1992; Niebur, Koch, & Rosin, 1993) and in working memory (Hummel & Holyoak, 1997; Luck & Beach, 1998). According to this view, features become bound into a single object, as the neuronal populations that code for these feature dimensions start to fire synchronously, forming a cell assembly. Under such a view, multiple object representations are made possible by the activation of multiple cell assemblies, which fire asynchronously relative to each other. Such parallel activation, however, does not come without a cost, as they may lead to interference among the cell assemblies and subsequent degradation of object representations. Vogel, Woodman, and Luck (2001) present neural synchrony as the underlying basis to the storage limit of visual WM, as the simultaneous coding of 4-6 objects (Hummel & Holyoak, 1997) coincides with the 4 item bound observed in behavioral experiments.

By this token, neural synchrony may be used to explain the costs associated with manipulating information in working memory. Kessler and Meiran (2006) suggest that every time a stored object is manipulated, the respective cell assembly coding for that object must first undergo desynchronization. During this period, the object representation may become unstable, while the manipulation is performed. This may include the integration of a different combination of neurons coding for a feature value into the cell assembly. Once the manipulation is performed, stability is achieved once more through resynchronization. The costs observed with manipulating representations may emerge during this resynchronization process. Neuronal population A (color for object 1) may come to synchronously fire with Neuronal population B (location for object 2) and vice versa, leading to the non-target confusion errors observed in the dynamic change detection task. Moreover, during this resynchronization process, neuronal populations may fail to resynchronize with each other, leading to the loss of information and random guesses observed in the dynamic change detection task. Further investigation of this matter may reveal multiple costs in VWM manipulation.

The results observed in Chapter 2 suggest that there are costs associated with manipulating items in VWM. In the following chapters, I investigate how manipulation computations are affected by storage processes in VWM (Chapter 3) and vice versa (Chapter 4).

Chapter 3: What effect does VWM manipulation have on VWM storage?

3.1 Overview of Chapter 3

In the previous chapter, I demonstrated that there are indeed costs associated with manipulating information in VWM. However, it remains to be determined how these costs relate to those for storing information in the system. In Chapter 3, I address this issue by investigating the effects of manipulating on VWM storage. Specifically, I investigate what happens to memory for stored information once it has been manipulated.

Manipulating items in VWM may completely destroy a memory for the initial array – e.g., if memory is tied to object files and the objects move during manipulation. Relatedly, memory for the initial state may exist during manipulation, but might degrade as a function of the number of manipulations. This may occur via a gradual overwriting processes that serves to accommodate manipulated changes. Both sets of results would suggest that VWM storage and manipulation operate on the same representations.

In contrast, memory for the original stored representation may be preserved and unaffected by the number of manipulations performed. Data consistent with this pattern would support the existence of two separate representations in VWM. One representation may maintain information about the initiate state of items before they were manipulated. I refer to this as the “original stored representation”. Another representation may constitute the contents on which operations are performed and reflect the updated state of manipulated item. I refer to this as the "manipulated representation". Determining whether VWM storage and manipulation operate on the same or separate representations would prove fruitful towards developing models of the system.

In the following sections, I use variants of the dynamic change detection task to investigate the effects of VWM manipulations on memory for the initial state of stored objects. In Section 3.2, I determine the extent to which featural information of the memory display is maintained, after a series of manipulations have been performed (Experiment 5). In Section 3.3, I probe memory for both the initial and manipulated states of objects, by investigating their featural-spatial bindings before and after a series of manipulations have been performed (Experiment 6). Lastly, in Section 3.4, I investigate whether the costs associated with manipulating information in VWM affect information that is strictly stored in the system (Experiment 7).

3.2 Experiment 5 - Effects of VWM manipulations on memory for the initial state of stored objects: memory for featural information

Throughout the experiments described in Chapter 2, memory for the binding of featural-spatial information decreased as a function of the number of manipulations performed for set sizes 3 and 4. One possibility is that these findings reflect failures to update the *binding* of featural-spatial information – that is, participants know the colors but do not know the proper binding between color and position. Alternatively, these errors may emerge from featural information of the stored representations dropping out of memory with each swap (i.e. color information is lost with each manipulation).

In Experiment 5, I attempt to discriminate between these alternatives by testing memory for stored featural information after the occurrence of a series of manipulations. Specifically, participants manipulated information as in previous experiments. However, during the test phase, they were additionally instructed to report as many colors as they remembered being presented in the initial memory array. If VWM manipulations degrades/destroys memory for the specific colors involved in the initial display then I should once again observe a 2 vs. 3 and 4 accuracy pattern, whereas accurate memory for the original colors at all set sizes would suggest that VWM manipulations do not degrade the initial state of the to-be-manipulated items.

Methods:

Thirty-one participants completed 180 trials of a dynamic change detection task (with delayed identification response) identical to that used in Experiment 1b, with the following additional component. After participants clicked on the response bar to identify the color of the cued item, all of the stimuli presented on the screen disappeared except for the option bar. Participants were instructed to click on the option bar to indicate as many colors as they were certain of that had been presented in the initial memory display. These responses were used to gauge participants' memory for the featural information that was stored in VWM before this information had been manipulated.

Results:

The results of a 3 (set size) x 5 (number of swaps) within-subjects ANOVA conducted on target identification accuracy were similar to those observed in previous experiments (Figure 18). A main effect of set size was observed, $F(2,60)=67.19$, $p<0.001$, $\eta_p^2=.69$, such that accuracy was highest for set size 2 displays compared to set size 3, $F(1,60)=30.29$, $p<0.05$, and set size 4, $F(1,60)=82.41$, $p<0.05$. Accuracy for set size 3 displays were also higher compared to set size 4 displays, $F(1,60)=80.12$, $p<0.05$. The ANOVA also produced a significant main effect of number of swaps, $F(4,120)=28.12$, $p<0.001$, $\eta_p^2=.48$, where accuracy for the static condition was higher compared to the dynamic conditions, $F(1,120)=68.57$, $p<0.05$. Furthermore, a significant interaction of set size by number of swaps was observed, $F(8,240)=4.82$, $p<0.001$, $\eta_p^2=.14$. Once more, a significant linear (set size 2) x linear (set sizes 3 and 4) contrast, $F(1,240)=29.05$, $p<0.05$, provided support for differential effects in the manipulation of displays containing 2 items vs. 3 and 4 items.

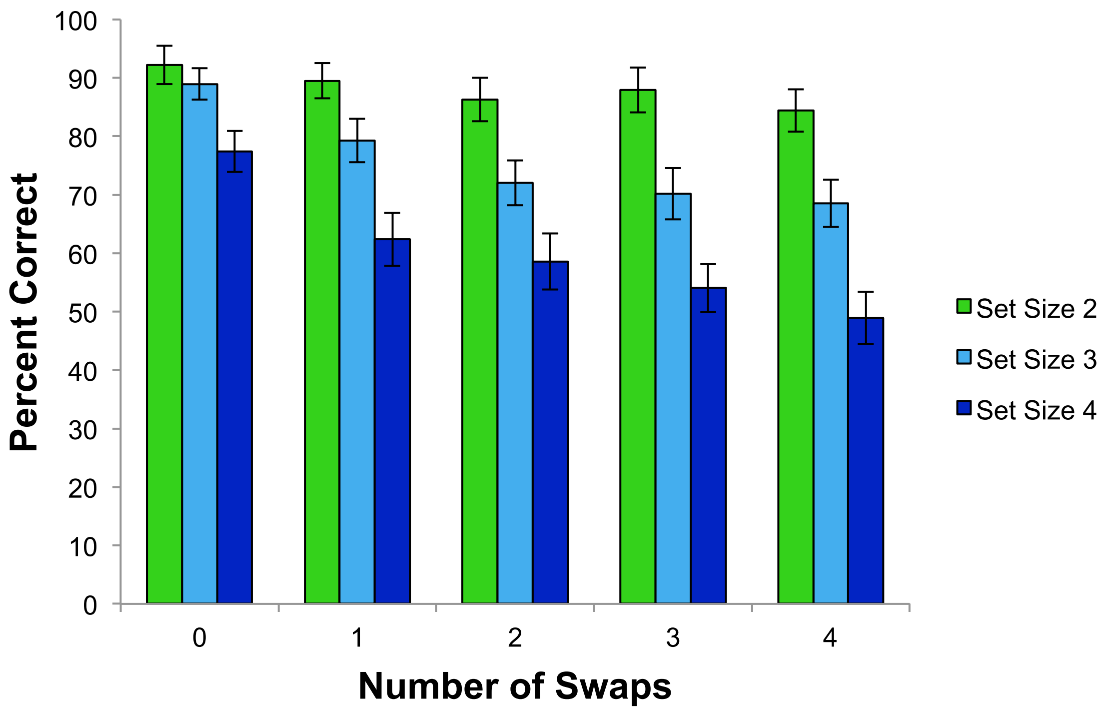


***Figure 18*. Results observed for target identification accuracy (percent correct) in Experiment 5 – dynamic change detection task (with delayed identification response method). This pattern is consistent with results observed in Chapter 2, where there is little-to-no cost for manipulating 2 items in VWM, whereas a systematic decrease is observed for manipulating 3 or 4 items.**

To investigate memory for the featural information presented in the initial memory display, I divided the total number of correct color identifications for that display by the set size of that display (number of color correctly recalled / total number of colors presented in display). This value represents the proportion of the display colors that were correctly recalled after a series of manipulations. For example, correctly recalling three colors that were part of a four-item display would yield a value of 75%. These values were calculated for all conditions and separated into two categories, depending on whether the target item had been correctly or incorrectly identified in that trial.

A 3 (set size) x 5 (number of swaps) within-subjects ANOVA conducted on these values for correct target identification trials (Figure 19) revealed a significant main effect of set size, $F(2,58)=56.88$, $p<.001$, $\eta_p^2=.66$. Post-hoc contrasts revealed that the highest proportions were observed in set size 2 trials (set sizes 2 vs. 3: $F(1,58)=29.20$, $p<.05$; set sizes 2 vs. 4: $F(1,58)=60.52$, $p<.05$) and the lowest were observed in set size 4 trials (set sizes 3 vs. 4: $F(1,58)=59.78$, $p<.05$). Across all set sizes, participants were able to correctly recall the majority of all feature values presented in the memory display (Set Size $2_{average}$=97.54%; Set Size $3_{average}$=92.35%; Set Size $4_{average}$=80.11%). In contrast, the ANOVA failed to produce a significant main effect of number of swaps, $F(4,120)=1.14$, $p=.34$, $\eta_p^2=.04$. This suggests that the proportion of featural information remembered from the initial memory display did not vary as a function of the number of manipulations performed. Once more, participants were able to report the majority of colors presented in the memory display, despite the number of swaps that had taken place (0 $Swaps_{average}$=90.49%; 1 $Swap_{average}$=90.49%; 2 $Swaps_{average}$=90.52%; 3 $Swaps_{average}$=88.75%; 4 $Swaps_{average}$=89.75%). The ANOVA also failed to produce an interaction of set size x number of swaps, $F(8,240)=0.84$, $p=.51$, $\eta_p^2=.03$.

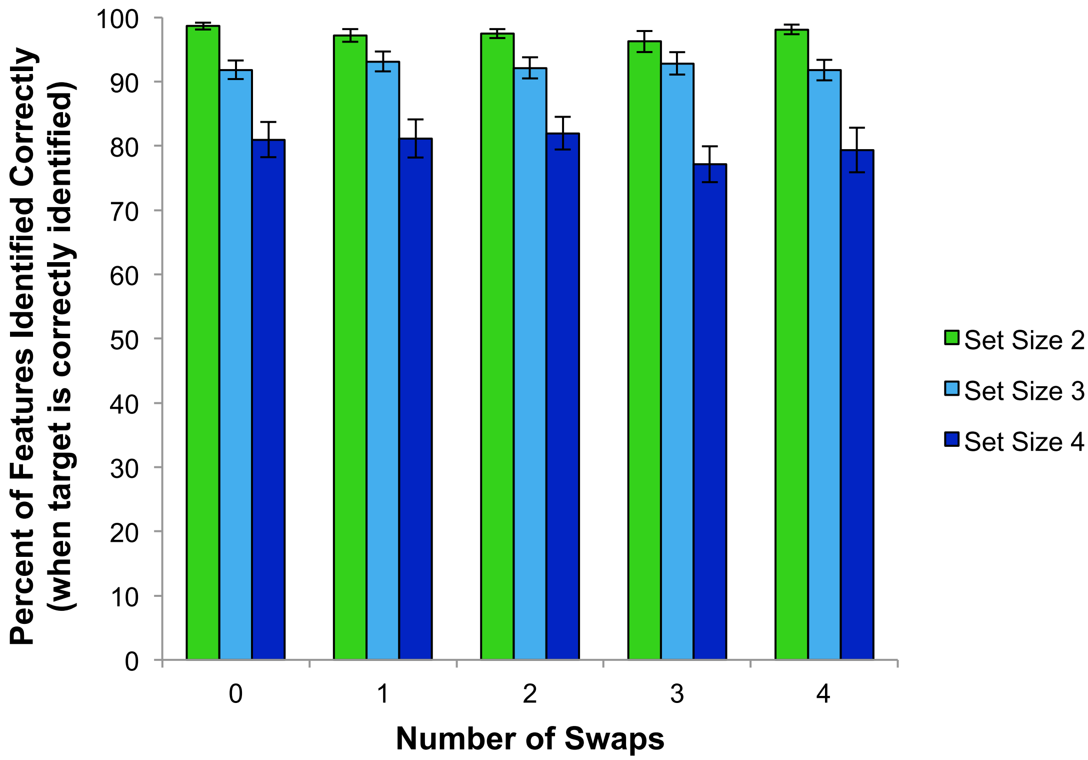


***Figure 19*. Percent of features presented in memory display that were correctly identified (for trials where the target was also correctly identified). Observers retained featural information presented in the memory display, despite systematic impairments to update the binding of these features to novel spatial locations for set sizes of 3 and 4 items (illustrated in Figure 18).**

3.3 Experiment 6 - Effects of VWM manipulations on memory for the initial state of stored objects: memory for featural-spatial bindings

Whereas a 2 vs. 3-4 item disparity is observed when manipulating information in VWM, no such pattern emerges when investigating memory for featural information that was part of the initial stored memory array (Experiment 5). Unlike performance for manipulated representations, memory for colors that were stored in the system was unaffected by the number of swaps that occurred.

However, the preservation of the stored featural information only reflects one aspect of the initial stored memory set. Is memory for the original featural-spatial bindings of objects in the initial memory array also unaffected by VWM manipulations?

In Experiment 6, I examine memory for the original state and manipulated state of featural-spatial bindings of objects, after a series of manipulation computations have been performed. In so doing, I investigate whether manipulating information in VWM completely overwrites, gradually overwrites, or has no effect on the memory for the initial state of stored objects.

Methods:

Twenty-three participants completed 540 trials of a modified dynamic change detection task (with a delayed identification response method) similar to that used in Experiment 1b. Once more, participants were presented with set sizes of 2-4 items. Pairs of items swapped 0-4 times. Dwell times were enforced (as in Experiment 3b) to ensure that all trials were equidurant.

Experiment 6 differed from previous experiments in one important way (Figure 20). In previous experiments, participants were only asked to indicate the identity of a probed stimulus after all swaps had occurred. In Experiment 6, participants were asked to indicate the identity of a probed stimulus after all swaps had occurred (manipulated state condition), on 45% of all trials. This question probed memory for the featural-spatial bindings of objects after they had been manipulated. On another 45% of all trials, participants were asked to indicate the original color that had appeared in the probed position *before* any swaps had occurred (initial state condition). This question probed memory for the initial featural-spatial bindings of objects before they were manipulated.

On the remaining 10%, no swaps occurred and participants were asked to indicate the color of the cued item. These static state condition trials also probed memory for the initial state of objects; this condition serves as a baseline measure, since trials of this type were not succeeded by manipulation computations.

The order of all condition trials was completely randomized. This required participants to maintain information about the initial memory array, while simultaneously updating featural-spatial bindings across swap movements.

During the test period, different texts (average of 1.7° x 0.85° of visual angle per letter, white) were presented above the option bar to indicate a probe for the initial state vs. manipulated state of objects. That is, the text directed participants to indicate the color of an item they expected to see at a cued location either "*before all swaps*" had occurred or "*after all swaps*" had occurred. During static condition trials, participants were presented with text displaying the word "color", instructing them to indicate the color of the cued item.

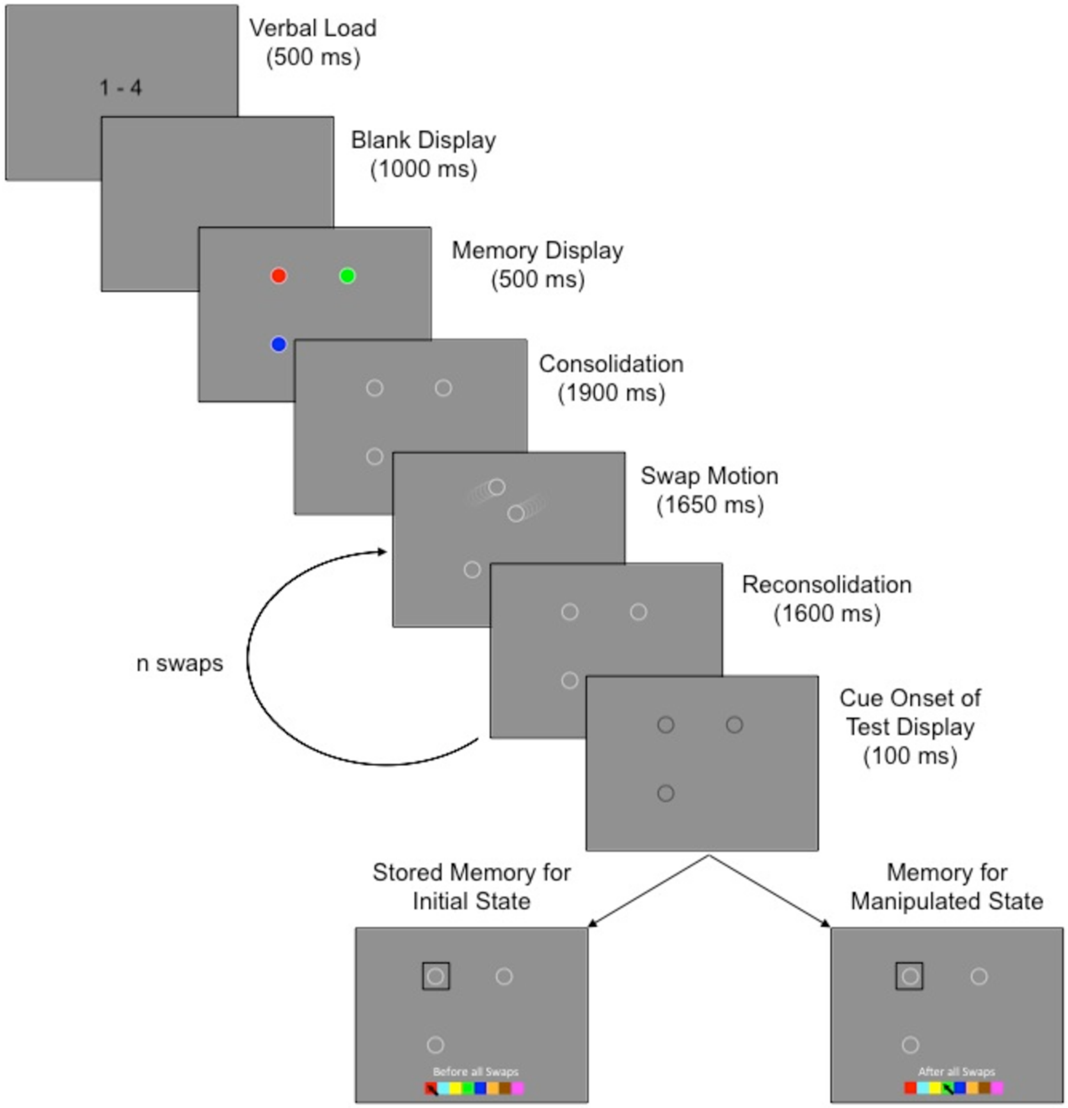


Figure 20. **Schematic of dynamic change detection task (with delayed identification response) used in Experiment 6. During the test phase of dynamic conditions, participants were instructed to report the identity of a cued stimulus either "Before all Swaps" had occurred or "After all Swaps" had occurred. For the static condition, participants were simply instructed to report the "Color" of the cued stimulus.**

Results:

To compare performance on static state trials with performance on initial and manipulated state trials, I collapsed performance across all swaps for the latter two conditions (Figure 21).

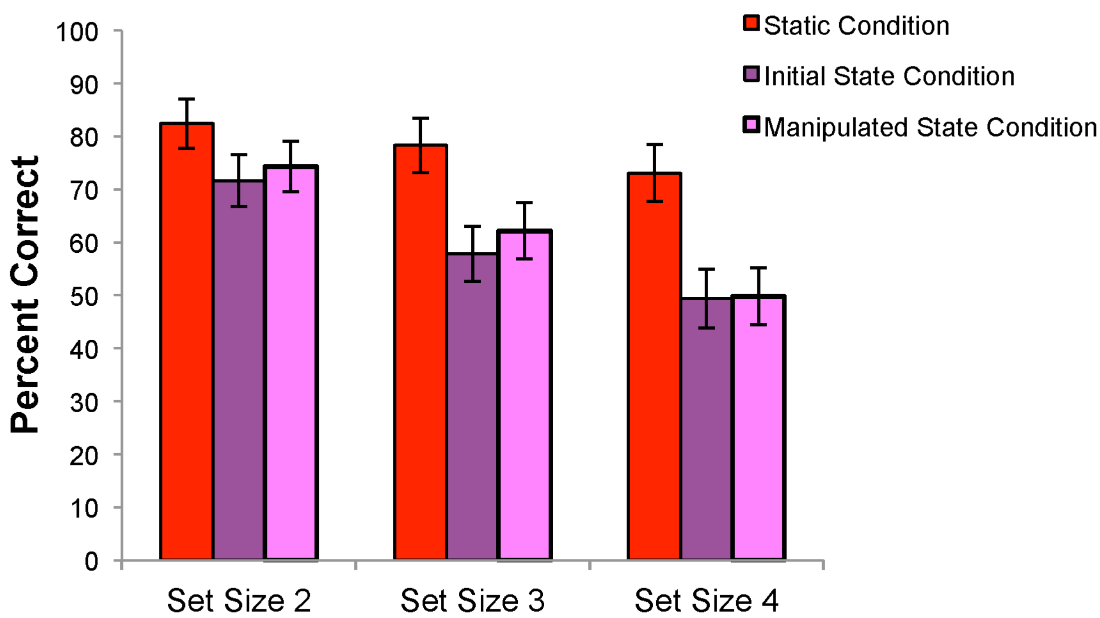


Figure 21. **Results (percent correct) collapsed across number of swaps in Experiment 6 – comparison of performance for static state, initial state, and manipulated state conditions. Accuracy is highest for the static state condition. No significant differences are observed in accuracy between the initial state and manipulated state conditions.**

A 3 (Set Size; 2, 3, 4) x 3 (Condition: static state, initial state, manipulated state) within-subjects ANOVA conducted on performance accuracy yielded a significant effect of Set Size, $F(2,44)=31.16$, $p<.001$, $\eta_p^2=.59$. Post-hoc contrasts revealed that performance accuracy was highest for Set Size 2 conditions (Set Sizes 2 vs. 3:

$F(1,44)=38.78$, $p<.05$; Set Sizes 2 vs. 4: $F(1,44)=69.13$, $p<.05$) and lowest for Set Size 4 conditions (Set Sizes 3 vs. 4: $F(1,44)=43.19$, $p<.05$.

Notably, the results illustrated in Figure 21 suggest that memory for the initial state of stored objects is preserved. Furthermore, the ANOVA yielded a significant main effect of Condition, $F(2,44)=56.44$, $p<.001$, $\eta_p^2=.72$, and post-hoc contrasts revealed that memory accuracy for static state conditions was higher compared to those probing the initial and manipulated object states, $F(1,44)=63.74$, $p<.05$. However, there was no significant difference in accuracy rates between initial and manipulated state conditions, $F(1,44)=0.98$, $p>.05$. It appears that accuracy is highest when no manipulation computations are performed at all. However, once participants manipulate information in VWM, memory for the initially stored and manipulated objects are affected equally.

The ANOVA also yielded a significant interaction of Set Size x Condition, $F(4,88)=8.19$, $p<.001$, $\eta_p^2=.27$. Post-hoc contrasts revealed that the accuracy differences observed between the static state condition vs. initial state and manipulated state conditions was smaller for Set Size 2 trials compared to Set Sizes 3 and 4 $F(1,88)=18.67$, $p<.05$. Furthermore, post-hoc simple main effect comparisons for static state condition trials demonstrated significant differences in accuracy rates between Set Sizes 2 and 3 vs. Set Size 4 conditions, $F(1,44)=11.74$, $p<.05$. These results replicate the 3-4 item storage limits that are prominent in the VWM literature (for review, see Brady, Konkle, and Alvarez, 2011). A similar analysis for the initially stored memory state yielded a significant difference in accuracy between Set Size 2 vs. Set Sizes 3 and 4 conditions, $F(1,44)=71.83$, $p<.05$. Lastly, post-hoc simple main effects for the manipulated memory array condition yielded a significant difference in accuracy between Set Size 2 vs. Set

Size 3, $F(1,44)=24.60$, $p<.05$, and Set Size 4 conditions, $F(1,44)=99.71$, $p<.05$. A significant difference was also observed between Set Sizes 3 and 4, $F(1,44)=24.60$, $p<.05$. These results for the manipulated representation reflect those observed in previous experiments in this dissertation.

Given the differences among patterns that emerged for these conditions, I also conducted an exploratory analysis where I separately investigated the pattern of results across set sizes and number of swaps for the manipulated and initial state of objects.

The results of a 3 (set sizes: 2-4) x 4 (number of swaps: 1-4) within-subjects ANOVA probing memory of the featural-spatial bindings of the manipulated objects produced a significant effect of set size, $F(2,44)=47.02$, $p<.001$, $\eta_p^2=.68$. A priori contrasts revealed that memory performance was highest for set size 2 (set sizes 2 vs.3: $F(1,44)=38.75$, $p<.05$; set sizes 2 vs.4: $F(1,44)=55.53$, $p<.05$) and lowest for set size 4 (set sizes 3 vs.4: $F(1,44)=33.65$, $p<.05$). This analysis also produced a significant effect of number of swaps, $F(3,66)=4.50$, $p=.006$, $\eta_p^2=.17$. An a priori contrast revealed an overall linear decrease in accuracy across number of swaps, $F(1,66)=11.13$, $p<.05$. Lastly, the ANOVA produced a significant interaction of set size x number of swaps, $F(6,132)=2.91$, $p=.01$, $\eta_p^2=.12$. Similar to our previous results, an a priori linear trend analysis revealed a significant difference in accuracy between set size 2 vs. set sizes 3 and 4 across the number of swaps, $F(1,132)=7.84$, $p<.05$.

In contrast, a different pattern of results was observed in the initial state condition, probing memory for the initial featural-spatial bindings of objects presented in the memory array. A 3 (set sizes: 2-4) x 4 (number of swaps: 1-4) within-subjects ANOVA produced a significant effect of set size, $F(2,44)=40.55$, $p<.001$, $\eta_p^2=.65$. A priori comparisons revealed that performance was highest for set size 2 (set sizes 2 vs.3: $F(1,44)=34.96$, $p<.05$; set sizes 2 vs.4: $F(1,44)=51.99$, $p<.05$) and lowest for set size 4 (set sizes 3 vs.4: $F(1,44)=19.27$, $p<.05$). However, the ANOVA failed to reveal a significant effect of number of swaps, $F(3,66)=2.49$, $p=.07$, $\eta_p^2=.10$, nor any interaction of set size by number of swaps, $F(6,132)=1.60$, $p=.15$, $\eta_p^2=.07$, suggesting that memory for the initiate state of to-be-manipulated objects remains unaffected by the number of manipulations performed. This stands in contrast to the pattern consistently observed in the manipulated state condition (e.g., Experiments 1-6).

3.4 Experiment 7 - Separation of storage and manipulation costs

The results of Experiment 6 suggest that manipulating items in VWM does not overwrite memory for the initial (pre-manipulated) state of the stored objects. For example, post-hoc simple main effects demonstrated differences in accuracy across set sizes for initial state vs. manipulated state conditions. Further differences between memory for the initial and manipulated state conditions were identified as a function of the number of manipulations performed. The results of Experiment 6 suggested that the memory for the initial state of the items remained intact, and did not degrade as the number of manipulations increased, however, the design of the Experiment 6 was not conducive for examining this issue due to two main reasons. First, the resulting 2 (initial state vs. manipulated state) x 3 (set size) x 5 (number of swaps) within-subjects ANOVA suffered from a lack of statistical power, given the number of conditions presented.

Second, and more importantly, the "dual task" demands that this experiment placed on observers (i.e. remember both the state of objects before and after they were manipulated) may have pushed participations to adopt a strategy where more emphasis was placed on manipulating items across swaps, compared to maintaining their initial state bindings in memory. Such a prioritization strategy might have masked any differences that could exist in the memory for the initial state across number of swaps. It could also explain the why accuracy in the initial state condition was lower compared to the static state condition – as soon as a single manipulation computation was required, focus may have been taken away from memory for the initial state of stored objects, producing some cost.

The dynamic change detection task used in the following experiment (Experiment 7) provides a more elegant way of investigating the effects that increasing number of manipulations may have on the initial state of objects that are stored in VWM. In this task, participants were *not* instructed to remember both the initial and manipulated states of objects. Instead, they were instructed to update the featural-spatial bindings of objects as they moved across the screen, just as in experiments described in Chapter 2. However, in Experiment 7, the number of times that the target item had to be manipulated was controlled systematically. Trials where manipulation computations were performed - but the target item did not participate in any swaps (target itself was not manipulated) – represented memory for the initial state of an object stored in VWM. These "0 participation" conditions provide a way to investigate whether manipulating (non-target) objects in VWM affects memory for objects that are merely stored in the system but not manipulated.

Methods:

Twenty-six participants completed 150 trials of a dynamic change detection task (with probe response method) similar to that used in Experiment 1a, with the exception that participants were always presented with a set size of 4 items. Once more, the number of swaps within each trial ranged from 0 to 4, and dwell times were enforced to ensure that all trials were equidurant. Most importantly, the number of times that the target item participated in a swap differed across conditions. Here, objects that can be conceptualized as merely being stored in VWM (and not manipulated) are those that do not participate in any swaps (0 participation conditions).

This design is illustrated in the right angle matrix presented in Table 1. For example, imagine a trial in which participants are presented with items A, B, C, and D where item D is cued as the target in the test display. In a 1 swap trial, item D can participate in 0 swaps (e.g. A and B swap, D remains stationary) or 1 swap (e.g. A and D swap positions). In a 4 swap trial, item D can participate in 0 swaps (e.g. A and B swap, A and C swap, C and B swap, A and B swap) or can participate in 1-4 swaps (4 participation example: D and A swap, D and B swap, D and A swap, D and C swap). This unbalanced design results from the restriction that the maximum number of times that an object participates in a swap cannot exceed the number of swaps that take place. Though the current investigation focuses on 0 participation trials, an equal number of trials was tested for all cells in this matrix, to ensure that participants were not able to predict which item would serve as the target. Note that the resulting unbalanced condition design does not prove problematic, since the *interaction* of number of participations x number of swaps is not of interest here. Instead, this design provides an elegant way of investigating the extent to which manipulation computations affect stored object representations, without placing dual-task demands that may lead to various performance strategies.

	Number of Swaps				
Number of Participations	*0*	*1*	*2*	*3*	*4*
	0	0	0	0	0
		1	1	1	1
			2	2	2
				3	3
					4

***Table 1.* Right angle matrix representing design of Experiment 7 (number of swaps x number of participations)**

Results:

To investigate memory for objects merely stored in memory, I conducted a single factor (number of swaps) within-subjects ANOVA on performance accuracy observed across all 0 participation trials (Figure 22, red bars). This analysis failed to produce a significant main effect of number of swaps, $F(4,100)=1.65$, $p=.19$, $\eta_p^2=.06$. This suggests that the total number of manipulation computations does not affect a stored representation that is itself not manipulated.

Furthermore, to investigate whether the presence of any manipulations performed in VWM affect items that are themselves not manipulated, I compared accuracy rates observed in 0 participations conditions where no manipulations had taken place at all (0 swaps) vs. conditions where objects other than the target item had been manipulated a number of times (average of 1-4 swaps). A paired-sample t-test failed to produce a significant difference between these conditions, $t(25)=-3.60$, $p=.72$. To ensure that this null result truly reflects no difference between these conditions (and not a lack of power, for example), I calculated the Bayes factor for this comparison. This analysis strongly supported the null hypothesis with odds of 4.55 to 1, suggesting that the probability that there is no difference between the compared conditions is approximately five times likelier than the probability that a difference does exist. These results suggest that, memory for a stored item that is never updated (0 participations) but is presented in a set with items that are manipulated is comparable to memory for an item that is presented in a display that is not manipulated at all. Moreover, they may suggest that the difference in accuracy rates observed in the previous experiment between the static and initial state conditions may have resulted from dual-task demands, where participants shifted focus away from information stored in VWM as soon as they had to perform a manipulation.

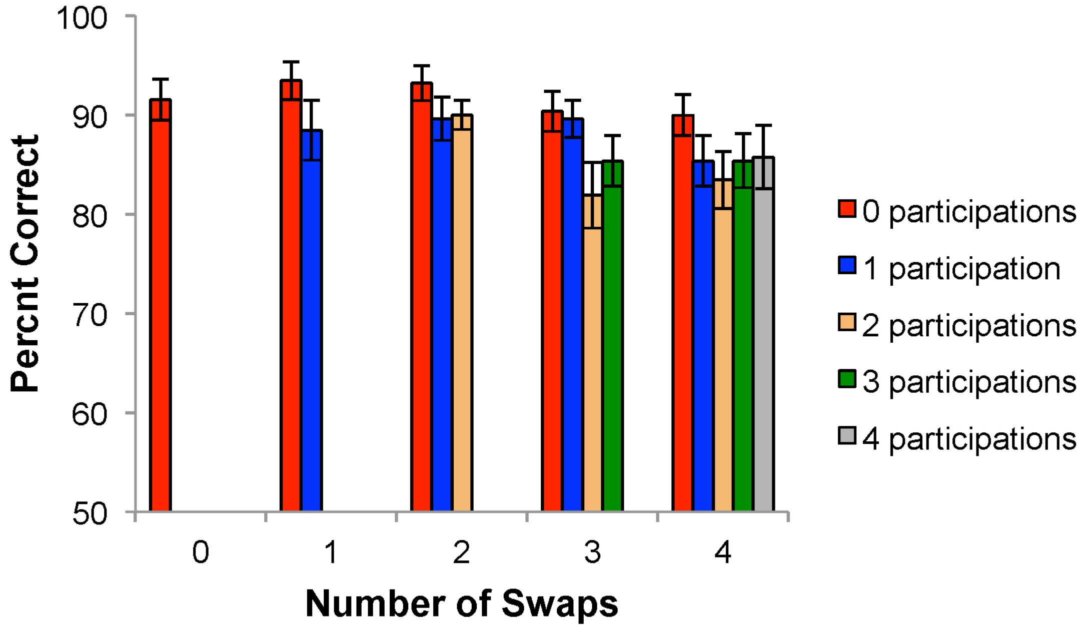


***Figure 22*. Results (percent correct) observed in Experiment 7 – effect of number of participations on manipulation costs.**

<u>Exploratory Analysis:</u> Effect of number of participations within each number of swap condition

What else may behavioral performance observed in Experiment 7 suggest about the costs of manipulating information in VWM? Collapsing data across all number of participations conditions replicates the results observed in Experiments 1-6, where performance accuracy decreases as a function of the number of swaps. A more refined hypothesis with respect to manipulation costs might be the possibility that memory for an object representation degrades as a function of the number of manipulations it participates in. While the unbalanced design of the experiment does not allow for a formal statistical analysis, the data illustrated in Figure 22 may support this hypothesis.

However, caution is necessary when interpreting these results for the following reason. In order for an object to be involved in more participations, the design of Experiment 7 stipulates for that object to be part of a condition where more swaps occur. Therefore, it is possible that Figure 22 simply recapitulates manipulation costs that are produced by the number of swaps. A different design is necessary to tease apart these costs from those associated with the number of participations.

3.5 Discussion

The results of Experiments 5-7 suggest that manipulating information in VWM does not affect memory for the initial state of objects stored in the system. Moreover, items that are not manipulated at all seem to be unaffected by costs associated with performing such computations. These findings may suggest that VWM storage and manipulation operate on separate representations. Whereas, the "original stored representation" may reflect the state of items before they were manipulated, the "manipulated representation" may reflect the state of items as they are operated upon. A theory for the underlying structure of these two separate representations may make contact with an ongoing debate in the VWM literature that focuses on the format of representations in the system. Though the following sections are highly speculative, exploring these hypotheses may prove fruitful towards connecting this work to a broader literature.

Perceptually Rich, Original Stored Representations vs. Abstract/Proposition-based, Manipulated Representations:

Whether representations stored in VWM should be conceptualized as perceptual photocopies or as abstract descriptions has been a point of contention. Theories such as the Sensory Recruitment Hypothesis support the former scenario, arguing that the neural mechanisms involved in the encoding of sensory stimuli are also recruited when information is maintained in memory over short periods of time (Harrison & Tong, 2009). By extension, contents in VWM are argued to simply be sustained perceptual photocopies. This claim is supported by neuroimaging evidence demonstrating that activity in primary visual cortex (V1) can be used to predict the orientation of gratings that are maintained over short temporal durations (Harrison & Tong, 2009). Similarly, differential patterns of activity in V1 can be used to predict which specific dimension of a multi-feature item is stored in VWM (Serences et al., 2009).

Opposition to the Sensory Recruitment Hypothesis stems from arguments that conceptualize stored representations as propositional in nature (Halberda, personal communication; Pylyshyn, 1981, 2003). In such proposals, the contents stored in VWM are descriptions/interpretations of the initial visual input. This format could facilitate the compression of information in the system and prevent information overload by eliminating the need to store perceptual details (a description would suffice). Studies illustrating subjective biases demonstrated in VWM paradigms may provide evidence supporting the claim that VWM representations are interpretations of perceptual input (Bae et al., 2015; Diedrichsen et al., 2004).

One exciting speculation is that these two hypotheses may not be mutually exclusive, as evidenced by the distinction between the initially stored and manipulated representations. Specifically, the original representation may be a sensory photocopy that is rich in perceptual detail. In contrast, the manipulated representation may be more abstract and propositional-based. But why would VWM need to have two separate representations that coexist and differ in format?

To answer this question, I emphasize that storing information in VWM is a selective process (Drew & Vogel, 2009). Items are maintained in a privileged state of activation so that they can be used/operated upon to guide intelligent behavior. Even aspects of an object or a display can be selectively stored, if those specific attributes are thought to serve the current goal (Woodman & Vogel, 2008). A propositional representation may provide a format that allows for information presented as part of a larger set to be extracted and used for a particular operation whereas a perceptual photocopy may not be as selective (but see Serences et al, 2009). By using a description of an object for a computation, VWM may avoid any information overload that would result from operating on a perceptually rich representation. However, given that our goals are constantly changing, we may need to retrieve other aspects of an item that come to be task relevant. Having a separate representation that is perceptually rich may allow individuals to probe memory for original stored contents that may have previously been deemed unnecessary to extract. The extracted perceptual information may flexibly be transformed into a propositional code, allowing for them to be manipulated. This may suggest that individuals can hierarchically move across these representations.

Furthermore, if an individual wants to conduct multiple non-additive manipulations, having memory for the original stored content provides a way to perform each subsequent computation afresh. For example, imagine if you're deciding whether your shirt would look better with a spaghetti stain across the chest or with a flower on the right sleeve. You are able to manipulate what your shirt would look like under these different scenarios without combining information from each representation (i.e. when envisioning the second scenario, you do not think about your shirt as having a red stripe *and* a flower on the right sleeve). Simply put, changes resulting from a preceding manipulation do not bleed into a subsequent manipulation computation. As such, having two separate VWM representations would provide the flexibility needed to manipulate information in one way and then perform a different set of manipulations, based on changes in current goal states.

These hypotheses provide an explanation of why VWM would need to preserve memory for the original state of items and why these original stored representations may have a perceptual format. But what benefit would a propositional format provide for manipulated representations? A representation that is propositional in format may provide the flexibility necessary to allow for a variety of cognitive computations to be performed on these representations. Though the manipulation computations focused on in this dissertation pertain to the updating of featural-spatial information, we are able to perform a wide variety of manipulations. These computations range from updating quantity information (Feigenson & Yamaguchi, 2009; Oberauer, 2002) to integrating displays across multiple saccades (Irwin, 1991; Hollingworth & Henderson, 2002). Contents that are to-be-manipulated in VWM must be represented in a format that allows it to be compatible with a wide range of operations. A perceptually rich imagistic format may not provide the flexibility that is necessary. However, a propositional representation of objects may suffice (Halberda, personal communication) and allow for the contents in VWM to harmonize with other cognitive systems (e.g. long-term memory, verbal working memory, etc.).

Existing Evidence for Two Separate Representations in VWM:

Though the aforementioned hypothesis requires further investigation, data from published studies may be reinterpreted as supporting these claims. For example, Ackerman and Courtney (2012) measured neural activity under conditions where information was stored in VWM. Participants were instructed to either maintain representations of items or representations of relations between these items. Whereas greater activity was observed in the *posterior* portions of the prefrontal cortex and the intraparietal sulcus during the maintenance of item information, activation was higher in the *anterior* regions of these areas during the maintenance of relational information. The authors interpret these findings as demonstrating a dissociation between sensory (item) and abstract (relational) representations in VWM.

I reframe these results within the context of my proposed model. Specifically, the item based information may be an instance of what I refer to as the original stored representation, and the relational information may be more similar to a manipulated representation. Specifically, for relational information to be extracted from item based representations, the original representation may need to be transformed into a propositional code. The transformation of information from one format to another can be considered a type of manipulation.

A follow up study conducted by Ikkai and colleagues (2014) recorded neuronal oscillatory activity using electroencephalogram during a working memory task where participants had to maintain item or relational information. Specifically, they investigated activity in the alpha frequency band, which is thought to represent inhibitory activity. Relative to item trials, they found that the maintenance of relational information was associated with increased alpha inhibition in the posterior cortex. Given Ackerman and Courtney's (2012) findings that the posterior cortex represents sensory information, Ikkai and colleagues (2014) concluded that relational representations in working memory suppress sensory representations.

If the original stored and manipulated representations respectively correspond to item and relational representations, this may suggest that accessing one representation may require inhibiting the other. This may be required if information from one representation type presents as source of interference for the other. For example, the difference in accuracy between the initial state and static conditions in Experiment 6 may have resulted from interference by the manipulated representation. For example, if the original representation of an object places it at location A, but the manipulated representation of the object places it at location B, interference from one representation to the other would produce incorrect responses. This may explain why no differences in accuracy were observed across all 0 participation conditions in Experiment 7, due to the absence of conflicting information (either both original stored and manipulated representations place object A at the same location, or there is no manipulated representation for that object). Further investigation is required to determine how separate individuals are able to keep these representations and how easily they can move across this hierarchy.

Though these claims are highly speculative, further investigations pairing the dynamic change detection task with measures of neural activity may provide the necessary evidence to aid theory building. For example, differential brain activity observed when participants are asked to report the identity of an item at a specific location *before* or *after* a number of swaps are performed (as in Experiment 6) may demonstrate that separate regions are activated when probing memory for the original stored vs. manipulate representation. Moreover, a dissociation in activity observed in the anterior vs. posterior prefrontal cortex based on these conditions may further connect my work to a larger body of the literature. Nonetheless, the possibility that two separate types of representations may exist in VWM opens an exciting realm of possibilities for further investigations.

Chapter 4: Do factors that constrain Visual Working Memory storage additionally constrain manipulation ability?

4.1 Overview of Chapter 4

The results observed in the previous chapter suggest that manipulating in VWM produces little-to-no cost for representations that are simply stored in the system. This supports the claim that storage and manipulation computations may operate on separate representations. Under this framework, factors known to constrain VWM storage should not additionally constrain manipulation ability. These factors may constrain the (stored) information on which manipulation computations are performed, but should not exacerbate manipulation costs. In Chapter 3, I investigate this issue by determining whether factors known to constrain VWM storage additional constrain VWM manipulation.

To this end, I focus on the effects of information load on manipulation ability, as this factor has been suggested to limit VWM storage capacity. Across two experiments, I present participants with dynamic change detections in which memory stimuli vary in information load. In Experiment 8 (Section 4.1), I vary information by instructing participants to store and manipulate either one or two featural dimensions of a multi-feature stimulus. In Experiment 9 (Section 4.2), I vary information load by using stimuli from categorically different classes that vary in visual detail. These experiments provide insight into the role of storage limitations on manipulation ability.

4.2 Information Load and Manipulation Ability: Single-Feature vs. Conjunction Conditions

Static change detection tasks have been used to investigate limits in VWM storage capacity. In these tasks, adults are equally accurate at detecting featural changes for displays containing from one to four objects that vary on a single dimension (e.g. color). However, with displays containing more than three to four objects, their performance drops precipitously (Luck & Vogel, 1997; see also Pashler, 1988; Phillips, 1974; Pylyshyn & Storm, 1988; Scholl & Xu, 2001; Sperling, 1960; Vogel, Woodman & Luck, 2001). This decrease in performance is typically taken as evidence that the observer's VWM storage limit has been exceeded.

How are these storage limits affected by information load? Luck and Vogel (1997) conducted a static change detection task in which memory arrays consisted of colored lines with varying orientations. In single-feature conditions, participants were instructed to store *either* color or orientation information. In the conjunction condition, participants were instructed to store *both* the color and orientation information. By this token, the overall information load in the conjunction condition was twice as high as that in the single-feature conditions. Luck and Vogel (1997) found no difference in accuracy between single-feature and conjunction conditions. Performance accuracy was relatively constant up to four items, after which it decreased precipitously.

Very few studies, however, have been able to replicate this null result. Overall information load has been demonstrated to constrain storage abilities in tasks involving bicolored squares (Wheeler & Treisman, 2002), simple objects with features from the same dimension (Xu, 2002), and categorically different objects (Alvarez & Cavanagh, 2004). Results similar to those observed by Luck and Vogel (1997) have been observed in studies whose stimuli vary in color and orientation (Fougnie, Asplund, & Marois, 2011; Olson & Jiang, 2002).

To investigate the effects of information load on manipulation ability, participants in Experiment 8 were presented with memory arrays consisting of colored lines that varied in orientation. Participants were instructed to remember and manipulate either the color or orientation information (single-feature condition) or both dimensions (conjunction condition). These stimuli were used to investigate first-hand whether information load does affect VWM storage, as performance observed in the static condition of the dynamic change detection task represents limits in storage ability. Additionally, performance across the dynamic conditions (1-4 swaps) provides a measure of manipulation ability. Differences in accuracy between single-feature and conjunction conditions across dynamic conditions represent the interaction of manipulation ability with information load.

Participants

Twenty Johns Hopkins University students with normal or correct-to-normal vision took part in the study in exchange for course credit.

Equipment

The experiment was conducted in a dimly lit room, and presented on a Macintosh iMac computer with a viewable area of 43.5 x 27 cm. Viewing distance was not fixed, but averaged about 60 cm.

Stimuli

As per previous experiments, the verbal load for each trial consisted of two black digits (1.7° x 0.85°of visual angle each) that were presented at the center of the screen. Memory arrays consisted of three colored lines that varied in orientation. The colors with which these lines could appear were randomly chosen without replacement from a set of four possible discrete colors (red, yellow, green, blue). Similarly, line orientations were randomly chosen without replacement from a set of four possible discrete orientations (0°, 45°, 90°, 135°). Each colored line (width: 0.25° of visual angle; height: 1.18° of visual angle) was framed by a circular white outline that had a diameter of 1.47° of visual angle and a thickness of 0.13° of visual angle. The locations of these stimuli corresponded to the three vertices of an imaginary equilateral triangle (width: 4.91° of visual angle; height: 4.25° of visual angle) situated at the middle of the screen.

Procedure

All observers participated in both the single-feature and conjunction conditions, in counterbalanced order. The single-feature condition consisted of one block (100 trials) where participants were instructed to remember only the color information presented in the memory display, and another block (100 trials) where they were instructed to only remember the orientation information. The conjunction condition consisted of two identical blocks (100 trials/block) where participants were instructed to remember both the color and orientation of items presented in the memory display.

Across all conditions (Figure 23), the beginning of each trial was marked with the onset of a central fixation cross (black, 0.5° x 0.5° of visual angle) that remained on the screen for 500 ms. After an interstimulus interval of 100 ms, the two-digit verbal load was presented at the same location for 500 ms. Participants were instructed to vocally rehearse these digits out loud throughout the course of the trial. After an interstimulus interval of 1000 ms, participants were presented with the memory display consisting of the three lines that varied in color and orientation. These items were presented for 500 ms, after which the colored lines disappeared to leave behind the white circular outlines. This display remained static for 1900 ms, ensuring that the color-orientation feature bindings were adequately consolidated (Treisman & Zhang, 2006). As per previous dynamic change detection tasks, these items could remain stationary (static condition) or pairs of items could swap positions up to four times (dynamic conditions).

The circular outlines changed in color (white to black) to signal the impending onset of the test display. After a period of 500 ms, a black square outline (2.45° by 2.45° of visual angle) was used to cue the target item. Participants were instructed to report the identity of the target by using the mouse to click on an option bar presented at the lower part of the screen. For single-feature color trials, the option bar consisted of all four possible colors with which the stimuli could have been presented. Similarly, for single-feature orientation trials, the option bar consisted of all four possible orientations. Lastly, for the conjunction trials, the option bar consisted of all sixteen possible color-orientation binding combinations (4 color values x 4 orientation values).

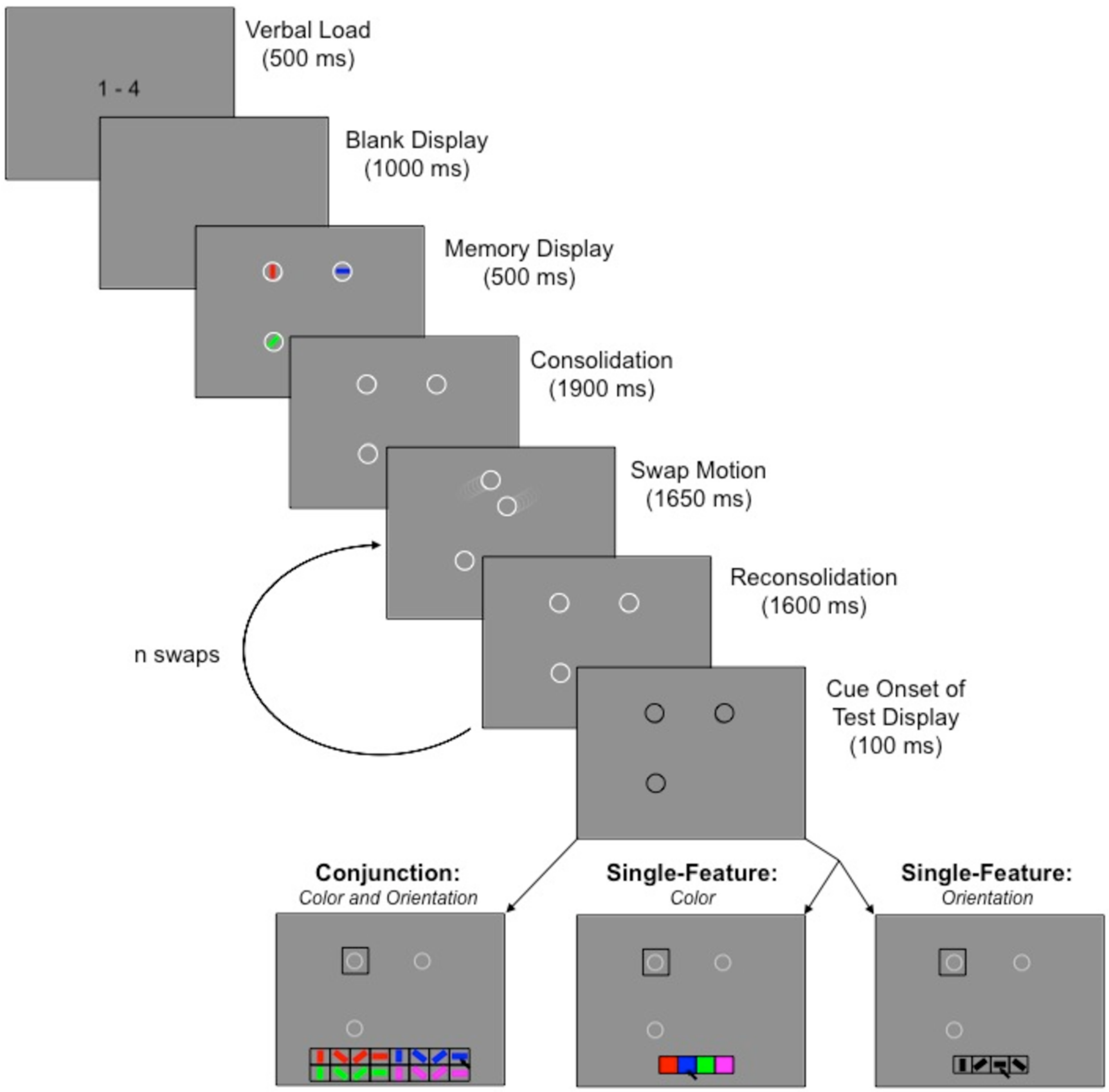


***Figure 23*. Schematic of dynamic change detection task (with delayed identification response) used in Experiment 8. All aspects of the paradigm were identical across all conditions, with the exception that participants were instructed to remember only the color or orientation information in the single-feature condition, as opposed to remembering both color and orientation information in the conjunction condition.**

Results

I first investigated whether any differences were observed in performance accuracy between color and orientation trials within the single-feature condition. A 2 (remembered feature) x 5 (number of swaps) within-subjects ANOVA failed to reveal a significant main effect of remembered feature, $F(1,19)=0.87$, $p=.36$, $\eta_p^2=.04$. Overall performance did not differ between color and orientation trials. As expected, the ANOVA did reveal a significant main effect of number of swaps, $F(4,76)=11.74$, $p<.001$, $\eta_p^2=.38$. Post-hoc contrasts revealed that accuracy decreased as function of the number of swaps, $F(1,76)=31.54$, $p<.05$. Once more, accuracy was higher in the static condition compared to the dynamic conditions, $F(1,76)=38.70$, $p<.05$. Lastly, the ANOVA failed to produce a significant interaction of remembered feature x number of swaps, $F(4,76)=1.18$, $p=.32$, $\eta_p^2=.06$. Taken together, these results suggest that manipulation ability observed in the dynamic change detection task did not differ across the featural dimensions used. As such, for comparisons against the conjunction condition, single-feature color and orientation conditions were averaged to produce an overall estimate of single-feature manipulation ability.

Given that the number of options presented in the option bar differed between the single feature and conjunction conditions, differences in guessing may have affected accuracy rates (random guessing = 1/4 vs. 1/16, respectively). Prior to comparing these conditions, I corrected accuracy rates for each condition in the following way (Equation 1a).

Assuming that memory ability across both conditions is equivalent, the numbers of trials on which participants correctly report the identity of the target based on genuine memory ability (x) should be equal. Differences between these conditions will result from the proportion of incorrect trials (n-m) where the participant guessed randomly (1/m) and chose the correct response. This proportion will vary based on the random guess rate.

<u>Equation 1a:</u>

Let:

- ***x*** = number of correct responses, based on memory ability
- ***n*** = total number of trials
- ***m*** = number of response options (e.g. 4 vs. 16)

$$\textbf{score} = \mathbf{x + (n\text{-}x)*(1/m)}$$

With a simple rearrangement of Equation 1a, performance accuracy for each condition can be corrected as follows (Equation 1b).

<u>Equation 1b:</u>

$$\mathbf{x = (m*score\text{-}n)/(m\text{-}1)}$$

Comparisons between single-feature and conjunction conditions were based on these corrected values. Note, whether random guessing rate in the conjunction condition is truly 1/16 or is 1/9 (i.e. participants remember 3 color and 3 orientation features presented in memory display and randomly guess among these options), the overall pattern of results (Figure 24) remains the same.

A 2 (single-feature vs. conjunction conditions) x 5 (number of swaps) within-subjects ANOVA yielded a significant main effect of condition, $F(1,19)=46.86$, $p<.001$, $\eta_p^2=.71$. Performance accuracy was higher for the single-feature condition compared to the conjunction condition. Furthermore, the ANOVA yielded a significant main effect of number of swaps, $F(4,76)=23.39$, $p<.001$, $\eta_p^2=.55$. Post-hoc contrasts revealed a linear decrease across the number of swaps, $F(1,76)=42.09$, $p<.05$. Once more, accuracy was higher in the static condition compared to the dynamic conditions, $F(1,76)=50.48$, $p<.05$. Most interestingly, the ANOVA failed to reveal a significant interaction of condition x number of swaps, $F(4,76)=0.67$, $p=.60$, $\eta_p^2=.03$. Taken together, these results suggest that information load affected storage abilities in VWM (0 swap condition), but that this factor did not additionally interact with manipulation ability.

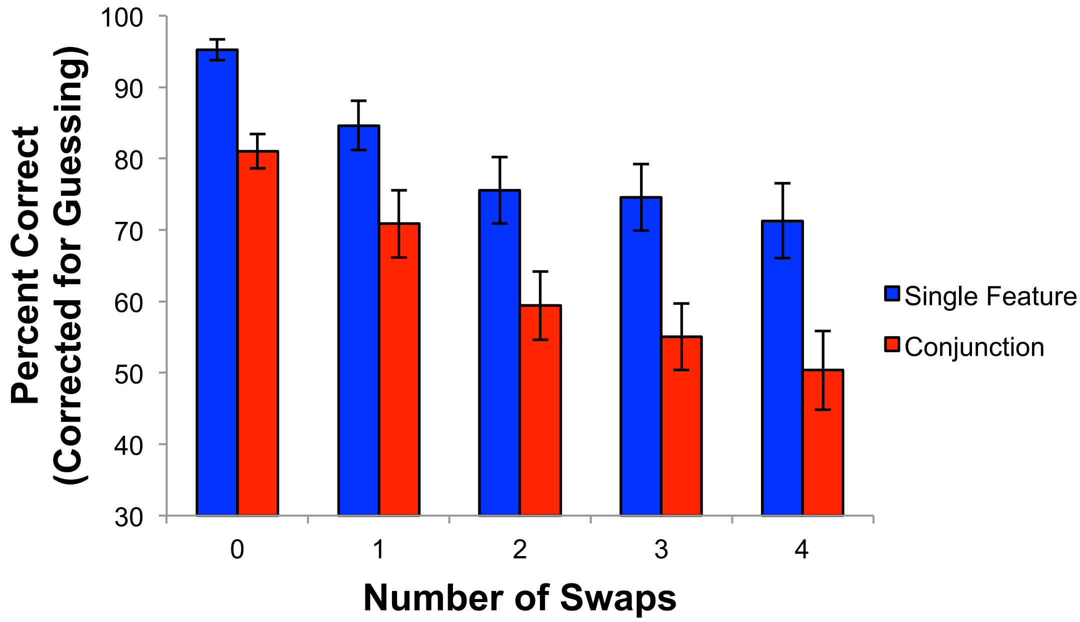


Figure 24. **Results (percent correct adjusted for guessing rates) observed in Experiment 8 – comparison of performance in single feature conditions (collapsed across color and orientation trials) vs. performance on conjunction condition.**

4.3 Information Load and Manipulation Ability: Complex Objects

The results of the previous experiment suggest that information load constrains the input on which manipulation computations act upon (stored information), but do not additionally exacerbate costs associated with manipulating in VWM. However, the failure to observe an interaction of manipulation ability with information load in Experiment 8 may be explained by the following alternatives.

First, observers were given an unequal number of options to choose from during the test phase in single-feature vs. conjunction conditions. Though the analyzed data were corrected based on the disproportionate rates of random guessing, having more options to choose from in the conjunction condition may have increased the number of comparisons that needed to be made and resultantly increased the amount of time taken to make a decision. Such increased demands in decision-making may have interacted with manipulation ability in a way to skew the true pattern of results. For example, accuracy across dynamic conditions in the conjunction condition may actually be equivalent. However, an increase in the level of decision-making difficulty may have interacted with the number of manipulations in such a way where performance accuracy decreased across the number of swaps. This decrement would not reflect manipulation costs, but rather, would be driven by factors associated with decision-making.

Second, information load in the previous experiment was operationalized by the number of features that had to be stored and manipulated in VWM. Specifically, conjunction conditions are thought to contain twice the amount of information compared to single-feature conditions, since participants had to remember information from two featural dimensions. However, using conjunctions of features that vary across two featural dimensions may have prevented manipulation costs from being exacerbated by information load. Specifically, it is possible that when conjunctions of features are manipulated in VWM, each feature dimension is represented separately [e.g. color information is stored in a color store and orientation information is stored in a separate information store (Wheeler & Treisman, 2002)]. Manipulation computations may then act on these representations in a parallel fashion. Such parallel processing may explain why an increase in information load did not seem to interact with manipulation ability.

In Experiment 9, I address these concerns by presenting participants with a change detection task, wherein the memory stimuli are sets of categorically different objects that vary in complexity. By this token, information load in this experiment is not operationalized by *the number of feature dimensions* that need to be encoded. Rather, information load "corresponds to the *amount of visual detail* stored for each object" (Alvarez & Cavanagh, 2004).

The stimulus set used in Experiment 9 consists of classes of objects that vary in complexity (colored squares, letters, Snodgrass drawings, and Kanji characters). These stimuli were identical to those used by Alvarez and Cavanagh (2004). In their investigation of the effects of information load on VWM storage capacity, information load for various stimulus classes was measured by processing rates in a visual search task. This was based on the notion that more informationally complex items will yield longer visual search rates, because they would have more details that would have to be encoded and compared. When these stimuli were presented in a static change detection task, Alvarez and Cavanagh (2004) found that VWM storage capacity decreased as a function of information load (accuracy: color > letters > Snodgrass drawings > Kanji characters > random polygons > shaded cubes). Out of the whole set in Alvarez and Cavanagh's (2004) study, the stimulus classes used in Experiment 9 (colored squares, letters, Snodgrass drawings, and Kanji characters) were chosen because participants were able to store at least three items of each category in VWM (participants can store approximately 2.0 random polygons and 1.6 shaded cubes).

Here, I use these four stimulus classes in a dynamic change detection task to investigate the effects of information load on manipulation ability. Given that the information load of the stimulus used varies as a function of visual detail within a featural dimension (and not by the number of independent feature dimensions that are to be remembered), performance accuracy cannot be explained using a parallel processing account. Furthermore, by using objects that vary in information load across stimulus classes, the number of options presented across all conditions, and resultantly demands placed on decision-making, can be held constant (i.e. each stimulus class has 8 possible exemplars).

Methods:

Participants completed 600 trials of a dynamic change detection task (with delayed identification response) identical to that used in Experiment 4a (Shapes), with the following exceptions. Each trial consisted of a set size of 3 items (each object subtended an average of 1.96° x 1,96° of visual angle), all of which belonged to the same stimulus category (Figure 25: colored squares, letters, Snodgrass drawings, or Kanji characters).

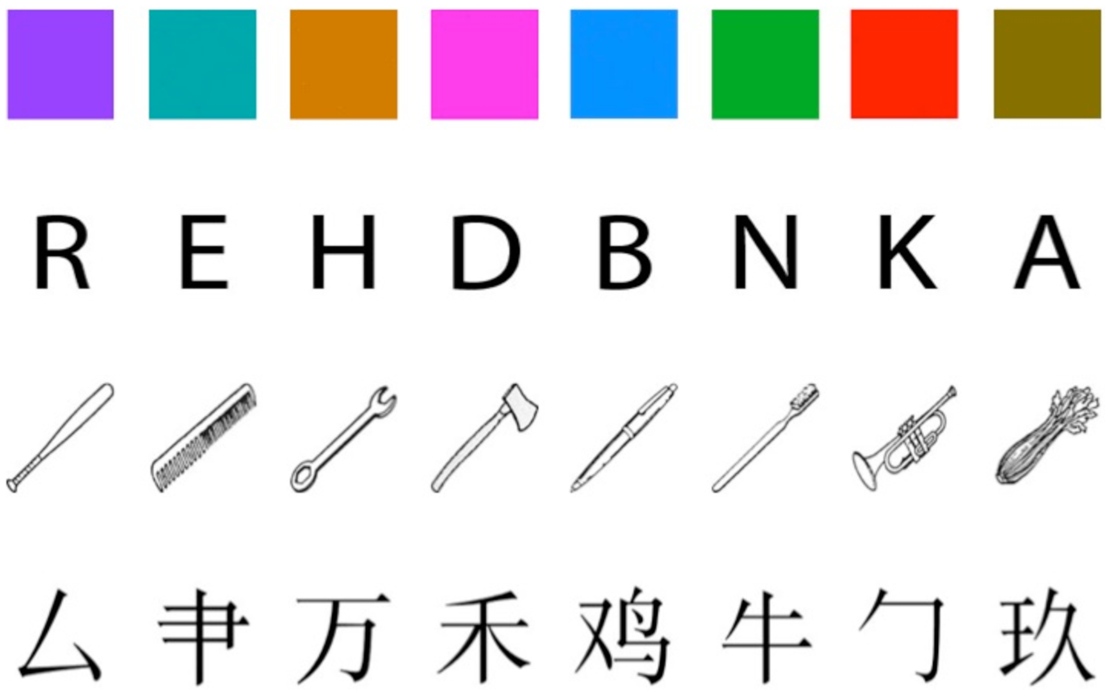


Figure 25. **Stimulus set used in Experiment 9 (includes 8 exemplars for each stimulus class: colored squares, letters, Snodgrass drawings, and Kanji characters).**

After the consolidation phase, black square placeholders were presented at the same location of these objects, giving the impression that the objects had been occluded. Pairs of placeholders could then swap positions 0 to 4 times. During the phase, the target item was cued by a black rectangular outline (3.93 ° x 3.93 ° of visual angle) and participants reported the identity this cued item by clicking on an option bar. The option bar presented on a given trial included the entire stimulus set for that class of objects (Figure 26).

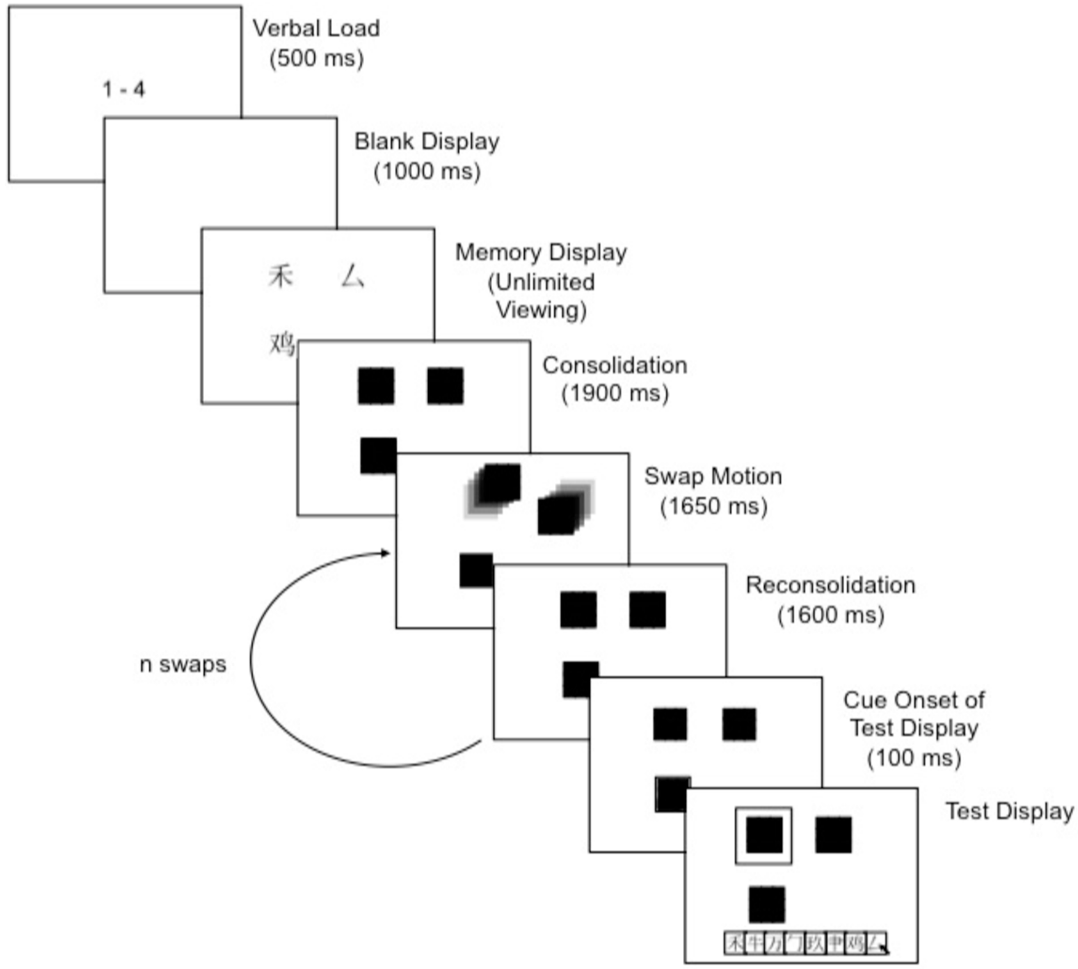


***Figure 26*. Schematic of dynamic change detection task (with delayed identification response) used in Experiment 9.**

Results:

The results of Experiment 9 are illustrated in Figure 27. A 4 (stimulus class) x 5 (number of swaps) within-subjects ANOVA conducted on performance accuracy yielded a significant main effect of condition, $F(3,36)=68.03$, $p<.001$, $\eta_p^2=.85$. Post-hoc contrasts revealed that memory ability was highest for letters (letters vs. colors: $F(1,36)=23.31$, $p<.05$; letters vs. Snodgrass: $F(1,36)=47.09$, $p<.05$; letters vs. Kanji: $F(1,36)=111.39$, $p<.05$). Second highest performance rates were observed for colored squares (colors vs. Snodgrass: $F(1,36)=32.61$, $p<.05$; colors vs. Kanji: $F(1,36)=97.24$, $p<.05$). Lastly, performance was lowest for Kanji characters (Kanji vs. Snodgrass: $F(1,36)=30.60$, $p<.05$). The ANOVA also produced a significant main effect of number of swaps, $F(4,48)=22.84$, $p<.001$, $\eta_p^2=.66$. Post-hoc contrasts revealed a linear decrease across all swap conditions, $F(1,48)=37.06$, $p<.05$. Once more, accuracy was highest in the static condition compared to the dynamic conditions, $F(1,48)=30.81$, $p<.05$. The ANOVA failed to produce a significant interaction of stimulus class x number of swaps, $F(12,144)=1.03$, $p=.41$, $\eta_p^2=.08$. The overall pattern of results observed here resembles those observed in the previous experiment (lines varying in color and orientation). These effects cannot be accounted by a parallel processing account and cannot be attributed to varying demands placed on decision-making processes. In short, it appears that Information load constrains storage, but not manipulation, ability in VWM.

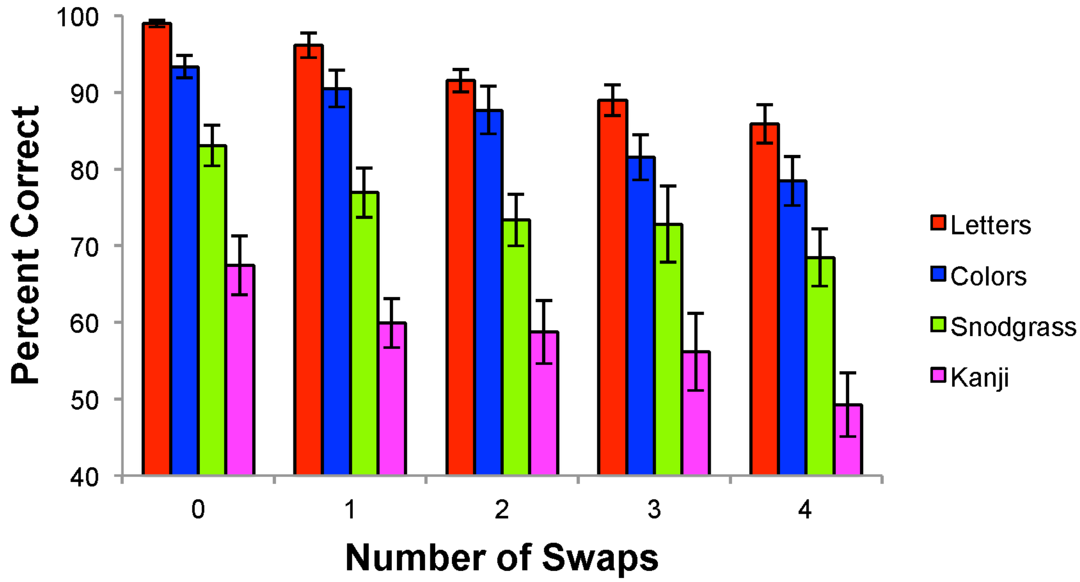


***Figure 27*. Results (percent correct) observed in Experiment 9 – comparison of performance across various stimulus classes differing in amount of visual detail.**

4.4 Discussion

Across two experiments, I demonstrated that information load affects VWM storage, but not manipulation ability. These findings compliment those reported in the previous chapter (manipulation costs do not affect stored representations), in supporting the argument that VWM storage and manipulation operate on separate representations. Further experiments demonstrating a null relationship between manipulation ability and other factors known to affect VWM storage would provide further evidence for this claim.

Despite the lack of interaction observed in Experiments 8 and 9, information load may affect manipulation ability in ways other than limiting the *quantity* of items that can be successfully manipulated. Many studies have demonstrated effects of information load on the *quality* of representations stored in VWM (Bays, Catalao, & Husain, 2009; Wilken & Ma, 2006). In these investigations, information load is operationalized as the number of simple featured items presented in the memory display, where a higher set size corresponds to a higher information load. The results of these studies suggest that an increase in the amount of information that needs to be stored in VWM negatively impacts the fidelity (precision) of these representations. However, pilot data from a dynamic change detection that I conducted demonstrates that precision is unaffected by the number of manipulations performed across all set sizes (2 to 4 items) and number of swaps (0 to 4 swaps). Nevertheless, further investigations are required to verify the null relationship between information load and manipulation ability.

The results of experiment 8 (single feature vs. conjunction conditions) provide converging evidence from various studies (Alvarez & Cavanagh, 2004; Wheeler & Treisman; Xu & Potter, 1999) that suggest information load limits VWM storage capacity. However, the fact that manipulation ability is unaffected by information load suggests that VWM storage strictly provides the input on which manipulation computations are performed. This opens up a whole new topic of investigation in VWM manipulations, with special emphasis placed on determining whether these computations are object-based or feature-based.

At first glance, the failure to observe interaction effects in Experiments 8 and 9 may be interpreted as evidence supporting an object-based account. Further investigations focusing on the types of errors participants make in these tasks may provide insight into this issue. Take for example, a dynamic change detection task in which the memory display contains a red vertical line and a blue horizontal line. When reporting the identity of the target item, participants may make whole object confusions (e.g. incorrectly choosing the red vertical line option instead of the blue horizontal line option), supporting an object-based account of manipulation. In contrast, participants may make feature-switch misbindings (e.g. incorrectly choosing red horizontal line option), supporting a featural-based account. Unfortunately, the 16 options provided in the conjunction condition used in Experiment 8 are not ideal for this analysis, given that the vast majority of options represent a bias for feature-switch misbindings options.

The binding of feature-feature information may also drive the appearance of object-based manipulations in Experiment 8. In a static change detection task, Treisman and Zhang (2006) demonstrated that the binding of two features occupying a single location becomes stronger as consolidation time increases (around 3 seconds). Specifically, at shorter consolidation times, each feature of an object comes to be linked with each other via respective bindings to a spatial location (Feature 1 → location ← Feature 2). As consolidation time increases, the role of spatial location as a mediating factor between these features decreases (Feature ←→ Feature 2). To demonstrate whether manipulations in VWM are object-based or feature-based, future investigations should vary consolidation times to decrease the strength of associations between features. If manipulations are feature-based, performance across the dynamic conditions for short consolidation trials should interact with information load and lead to feature-switch misbinding errors. Similarly, related investigations may use stimuli whose features do not occur at the same location or share the same contours (e.g. 2 textures that are side by side, or 2 conjoined color squares) to further investigate whether the occurrence of features at the same location leads to benefits in manipulation ability. Though the results of Experiment 9 provide evidence against this hypothesis (features did not occur at same location), further investigation is required to characterize the nature of manipulation computations in VWM.

Chapter 5: General Discussion

5.1 Summary

Exploring limits in working memory has proven instrumental towards characterizing the architecture of the system and the format of its representations. Specifically, costs associated with storing information in the system have been used to illustrate the central role that working memory plays in complex cognition, to establish it as distinct from other memory systems, and to demonstrate domain specificity within the system.

In my dissertation, I adopted a similar approach by focusing on costs associated with manipulating information. Though the term "manipulation" embodies a variety of operations, I focused on costs associated with spatially updating existing representations. First, I demonstrated that costs associated with updating the binding of featural-spatial information do exist and cannot be attributed to other factors known to constrain working memory (Chapter 1: Experiments 1-4). Next, I demonstrated that manipulating representations in the system does not overwrite the original stored representation (Chapter 2: Experiments 5-6), and that items that are merely stored (unmanipulated) are unaffected by manipulation costs (Chapter 2: Experiment 7). Lastly, given that manipulation ability does not seem to affect storage in VWM, I further investigated this distinction by asking whether a factor known to limit VWM storage (information load) affects manipulation. Across two experiments (Chapter 3: Experiments 8-9), I found that information load does not affect manipulation ability other than constraining the input on which manipulation computations are performed.

5.2 A working hypothesis of Visual Working Memory

I integrate these findings into a single framework, by offering the following working hypothesis. I suggest that there are two separate types of representations for items that are stored and manipulated in VWM. The first representation type, which I refer to as the original-stored representation, contains information about the items stored in VWM before they are manipulated. These representations may be sensory-based, perceptually rich, and perhaps supported by the anterior prefrontal cortex. The second representation type, which I refer to as the manipulated representation, contains the information on which mental operations are performed. This representation may be more abstract, propositional, and supported by the posterior prefrontal cortex. It is unclear whether this latter type of representation already exists when information is merely stored in the system or whether it is created as soon as a manipulation is performed.

I conceptualize the manipulated representation as a derivative of the original stored representation (hierarchically based). These representations may be separate, but not necessarily independent of one another. Further investigations are required to determine whether these representations come to be supported by other systems (e.g. the original stored representation may be supported by long-term memory) and to determine whether one representation type produces interference for the other (or whether individuals mistakenly probe the wrong representation type when making a response).

All objects that have been manipulated may incur a cost every time a manipulation computation is performed, even if that object is not being manipulated. The stored representation will be unaffected by these costs because it is indeed a separate representation (and the opposite is true for costs associated with storing information in the system). Further investigation is required to understand how easily participants may be able to move between the original and manipulated representations. Individual differences may exist in the strength of these representations, and future investigations correlating these measures with other indices of cognition may provide insight into how each representation type supports different aspects of cognition.

Lastly, manipulation costs may differ across various computations based on whether the operation relies more on abstract information of stored items (e.g. manipulating relational information) or perceptual information (color-spatial) information.

Though the framework I provide constitutes merely a working hypothesis, the results of the conducted experiments supports these ideas and opens up a new area of investigation for VWM research.

5.3 Relation to manipulation costs in Verbal Working Memory

Across Experiments 1-4, dynamically updating the position and color information for moving targets resulted in an additive cost with each movement for set sizes of both 3 and 4 targets. More interestingly, this cost was differentially influenced by the set size of stored items and the number of manipulations performed. The observed pattern of results is informative towards characterizing the structure of VWM. However, it remains to be determined whether such manipulation limits are unique to vision, or whether they reflect a more global executive function cost – perhaps, similar to that found in tasks of verbal working memory.

Studies within the verbal working memory literature have attributed manipulation costs to an internal mechanism analogous to serial attention (Oberauer & Bialkova, 2009; Oberauer & Hein, 2012). Within this framework, costs associated with manipulating information are actually selection costs that result from switching internal attention between stored representations (Oberauer, 2002, 2009). For example, in Garavan's (1998) updating task, participants had to keep a running count of the number of triangles and rectangles presented serially on a screen. The order with which these shapes were presented was intermixed, and participants were able to control the onset of each stimulus. Garavan compared the amount of time it took participants to initiate the onset of a stimulus after consecutively updating the two different counters (i.e. triangle was presented after a rectangle) or the same counter (i.e. triangle presented after another triangle). A manipulation cost was observed, as response times (RTs) were longer when participants had to consecutively update two different counters. Garavan (1998) explained the increase in RTs as resulting from bringing representations that were to-be-manipulated into a privileged state via shifts in serial attention (operating internally). As such, an internal mechanism analogous to selective attention may be used to select stored representations one at a time, so that they can be updated in some way. This "focused attention" mechanism may be used in the manipulation of both verbal and visual representations.

Such a selection mechanism may not be limited to a single item, but rather, to a single chunk. Oberauer & Bialkova (2009) used a dual-task paradigm (Oberauer, 2003) to demonstrate that working memory contents can be chunked together ad-hoc, when performing manipulations. In their task, participants had to temporarily store four numbers in working memory and perform an arithmetic operation on two of these numbers, at one time. Response latencies were recorded, and a benefit was observed when two numbers used in a given operation were also the same ones used for the operation on the previous trial. This was not the case when only one of these digits was repeated during two consecutive trials. Similar to Oberauer and Biakova's (2009) study, the items in the current study that are simultaneously manipulated during a given swap may be chunked into a single pair, such that both can be selected by the focus of attention. By this token, one would not expect to observe manipulation costs in the set size 2 conditions of the current study, because the same items would constantly be held within the focus of attention. In contrast, manipulating set sizes of 3 or 4 items would be expected to be costly, as the likelihood of breaking a chunk and switching different items into the focus of attention increases with every swap.

Selection costs associated with updating information have also been demonstrated in the visual domain. Throughout a series of experiments, Feigenson & Yamaguchi (2009) investigated infants' abilities to update the number of crackers sequentially placed in two buckets. They found that infants were able to successfully update quantity information when the crackers were hidden in direct succession (update bucket A, update bucket A again, then update bucket B), but not when the order of placement alternated between buckets (i.e. update bucket A, update bucket B, and update bucket A again). To ensure that the latter failure was not due to an increased demand in switching *external* attention between the two representations, the experimenters devised a condition in which infants had to attend to a different bucket but did not have to update that representation (i.e. update bucket A, experimenter waves hand behind bucket B to reorient attention, infant updates bucket A again, infant then updates bucket B). They found that infants succeeded in this condition, suggesting that the observed costs did not arise from having to switch external attention between the representations. This cost may be related to a switching of serial attention to access representations stored in VWM.

Though the manipulation of information in visual working memory may also involve an internal serial attention component, it is important to differentiate costs associated with selecting to-be-manipulated information vs. costs with performing actual manipulation computations. If attentional switch costs were at the root of the effect observed in the dynamic change detection task, allowing participants to control the onset of each swap (Experiment 2b) should have produced differences in RTs between set size 2 (maintain attention) vs. set size 3 and 4 (shift attention) conditions. This was not the case, as RTs in that experiment did not significantly differ from each other, suggesting that even in the absence of potential attentional switch costs, a separate manipulation cost persists. This may suggest that the selection of information and its subsequent manipulation might be separate processes. A limited internal attentional mechanism may be responsible for bringing items into a privileged state for them to be updated, but there very well may be a separate limited source that performs the manipulation computation.

Given the current state of the literature, it is difficult to assess the relationship between selection costs mentioned in the verbal working memory literature with the manipulation costs observed here. This is in large part due to the differences in the dependent measures used. Whereas selections costs are typically represented as retrieval differences reflected in RTs, we measured the effect of performing manipulations on the fidelity of the memory representation. Future investigations using comparable methods and measures would prove beneficial towards investigating the relationship between costs associated with manipulating verbal and visual information in working memory. Dual-task paradigms requiring the storage and/or manipulation of verbal and visual information would prove fruitful towards demonstrating whether working memory is entirely domain specific (i.e. information stored in separate modules) or whether verbal and visual manipulation abilities share a common resource or mechanism.

5.4 Concluding remarks

In short, my work with the dynamic change detection task paradigm has revealed some new phenomena for continued study (e.g., VWM manipulation costs and independence from storage costs) and it has opened new questions for inquiry in VWM, general working memory, and cognition at large. In the current dissertation, this paradigm was used to determine the relationship between limits in storage and manipulation abilities in visual working memory. The observed results emphasize that working memory is an active system, and that research must move beyond strictly investigating issues relating to storage limits. In this vein, investigations focusing on factors affecting manipulation abilities may provide further insight into the role of working memory in complex cognition.

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EDUCATION

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RESEARCH INTERESTS

- **Visual working memory**: limits in storage and manipulation abilities, individual differences, theory, interface with visual selective attention and long-term memory, neurophysiological markers of cognitive abilities (e.g. oscillatory activity, event-related potentials)

RESEARCH EXPERIENCE

The Johns Hopkins University, Psychological & Brain Sciences 2010-present
Hospital for Sick Children, Neurosciences & Mental Health 2007-2010
The University of Toronto, Cognitive Neuroscience Laboratory 2008-2009
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PUBLICATIONS

Published/In Press

Pailian, H., & Halberda, J. (2015) The reliability and internal consistency of one-shot and flicker change detection for measuring individual differences in visual working memory capacity. Memory & Cognition, 43, 397-420.

Pailian, H., & Halberda, J. (2013) Independent costs for storing and manipulating information in visual working memory. Visual Cognition, 21(6), 704-707.

Under Review

Pailian, H., Libertus, M., Feigenson, L., & Halberda, J. (under review). Visual working memory storage capacity increases between ages 3 and 8 years controlling for gains in exogenous and endogenous attentional control in a visual search paradigm.

Pailian, H., & Halberda, J. (under review). The costs of manipulating information in visual working memory.

Halberda, J, Simons, D.J., Wetherhold, J., **Pailian, H.,** &. (under review). The Flicker task provides converging evidence for a 3-item limit of visual working memory.

In Preparation (Available upon Request)

Pailian, H., & Halberda, J. (in prep). Individual differences in visual working memory manipulation ability.

Wilmer, J., **Pailian, H.**, & Halberda, J. (in prep). The nature, extent, and importance of human variation in change detection ability.

Pailian, H., & Halberda, J. (in prep). The relationship between costs associated with manipulating information in visual working memory and switching internal selective attention.

Pailian, H., Graves, T., & Egeth, H. (in prep). Evaluating the disengagement hypothesis of search modes using event-related brain potentials.

Pailian, H., Libertus, M., Feigenson, L., & Halberda, J. (in prep). Individual differences in working memory storage capacity and executive control measured using the Flicker paradigm.

INVITED TALKS

Pailian, H. (2014). The costs of manipulating information in visual working memory. Talk presented *at Brown University*, August 25, Rhode Island, MA.

Pailian, H. (2013). Constrains placed on executive control abilities in visual working memory. Talk presented *at The University of Toronto*, June 30, Toronto, ON.

CONFERENCE TALKS AND POSTER PRESENTATIONS

Pailian, H., & Halberda, J. (2015). Breaking visual working memory: independence between costs in storage and manipulation abilities. Talk presented *at VSS, the Vision Sciences Society*, May 15-20, St. Petersburg, FL.

Cunningham, C.A., **Pailian, H.,** & Egeth, H.E. (2014). Characterizing representations in activated long-term memory. Poster presented at the *Psychonomics Society* annual meeting, November 14, Long Beach, CA.

Pailian, H., & Halberda, J. (2014). On the dynamic nature of visual working memory: separate limits for the storage and manipulation of information. Talk presented *at VSS, the Vision Sciences Society*, May 16-21, St. Petersburg, FL.

Pailian, H., & Halberda, J. (2014). Dynamic nature of visual working memory across time and space. Talk presented *at VSS, the Vision Sciences Society* Satellite Event, May 16-21, St. Petersburg, FL

Graves, T., **Pailian, H.,** & Egeth, H. (2014). The role of rapid disengagement in overcoming attentional capture. Talk presented *at VSS, the Vision Sciences*

Society, May 16-21, St. Petersburg, FL.

Pailian, H., & Halberda, J. (2013). Independent costs for storing and manipulating information in visual working memory. Talk presented at the annual *Object Perception Attention and Memory* meeting, November 14, Toronto, ON, Canada.

Pailian, H. & Halberda, J. (2013). Moving beyond storage limitations: exploring the dynamic manipulation of representations in visual working memory. *Talk presented at VSS, the Vision Sciences Society*, May 10-15 Naples, FL.

Eisinger, R., Im, **H., Pailian**, H. & Halberda, J. (2013). Ensemble-based change detection. *Poster presented at VSS, the Vision Sciences Society.* May 10-15, Naples, FL.

Pailian, H., Libertus, M., Feigenson, L., & Halberda, J. (2013). Developmental changes in visual short-term memory (VSTM) capacity between Ages 3 and 8 Years. *Poster presented at SRCD,* April 18-20 Seattle, WA.

Pailian, H., Libertus, M., Feigenson, L., & Halberda, J. (2013). Measuring individual differences in children's visual short-term memory capacity using the Flicker paradigm. *Poster presented at SRCD,* April 18-20 Seattle, WA.

Wilmer, J. B., Germine, L., Ly, R., Hartshorne, J.K., Kwok, H., **Pailian, H.**, Williams, M.A., & Halberda, J. (2012). The heritability and specificity of change detection ability. *Talk presented at VSS, the Vision Sciences Society,* May 11-16, Naples Florida.

Pailian, H., & Halberda, J. (2012). The cost of manipulating representations in working memory. *Poster presented at VSS, the Vision Sciences Society,* May 11-16, Naples, FL.

Pailian, H. & Halberda, J. (2011). Individual differences in visual working memory capacity assessed by the Flicker task. *Poster presented at VSS, the Vision Sciences Society,* May 6-11, Naples, FL.

TEACHING

Positive Psychology (Co-Instructor)	Spring 2015
Psychology of War and Genocide (Instructor)	Intersession 2015
	Intersession 2014

<u>Teaching Assistant</u>

Positive Psychology (including part-time lecturer)	Fall 2013
Human Sexuality	Spring 2013
Positive Psychology (including part-time lecturer)	Fall 2012
Positive Psychology	Fall 2011

Foundations of Mind (including part-time lecturer)	Spring 2011
Introduction to Cognitive Psychology	Spring 2011

AWARDS & HONORS

Johns Hopkins University – Psychological and Brain Sciences ***Walter L Clark Teaching Award***	2015
Johns Hopkins University – Psychological and Brain Sciences ***Collaborative Research Award***	2015
Johns Hopkins University – Psychological and Brain Sciences ***Research Expansion Award***	2014
Johns Hopkins University – Psychological and Brain Sciences ***Collaborative Research Award***	2013
Johns Hopkins University – PURA Award (mentorship role)	2012
Johns Hopkins University – Psychological and Brain Sciences ERP Training Grant	2012
Natural Sciences and Engineering Research Council of Canada (NSERC) Alexander Graham Bell PGS-D	2011-2015
Natural Sciences and Engineering Research Council of Canada (NSERC) Alexander Graham Bell PGS-M	2010
University of Toronto's First Year Sexual Diversity's In Course Award	2009
Troy Najarian Memorial Scholarship	2008
Galust Gulbenkian Scholarship	2008
University of Toronto's Dr. Taverna Award	2007

SERVICE

Johns Hopkins University Colloquium Committee	2014-2015
Johns Hopkins University LBTQ Graduate Students'	2012-2014

Association, *President*